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ENERGY INSTITUTE
ENERGETICKÝ ÚSTAV

THE EARTHSHIP CONCEPT AND ITS ENERGY DESIGN
ZEMĚLOĎ A JEJÍ ENERGETICKÝ POTENCIÁL

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Assignment Bachelor's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

The Earthship concept and its energy design

Brief Description:

Climate change is one of the most pressing scientific and political challenges of our time. A main objective in doing so is by focusing on designing and constructing buildings that achieve resource efficiency, minimize water and energy consumption, as well as waste generation. The building sector has big potential to bring about deep, quick and long–term cost effective reductions of Green House Gases. A lot of energy and non–renewable resources used in “modern” building materials could be avoided by building with natural and local raw materials, as 80 to 90% of all the material waste flows is generated from reinforced concrete and steel. One example of an autonomous building concept is referred to as the Earthship. The Earthship concept originated in the 1970th, a time when Barbara Ward held her speech at the Stockholm “Only one Earth” conference. The core of the Earthship is the idea of building an “autonomous” building and combine trash and shelter, that is to say, two social needs. Therefore, it can be seen as an extreme building technique that uses as much immediately available resources as possible, and intends to not extend its building footprint beyond its means, enabling it to help its dweller to obtain a green lifestyle.

Bachelor's Thesis goals:

The aim of the thesis is describe the so–called Earthship as a self–sufficient building primarily intended for sustainable housing. The individual energy systems should be described in more detail, including a simplified calculation of the energy balance. The conclusion of the work should critically assess the advantages and disadvantages or limitations of the entire housing system.

Recommended bibliography:

COOK a GARRETT. Green Home Building: Money-Saving Strategies for an Affordable, Healthy, High-Performance Home. New Society Publishers, 2014. ISBN: 978-0865717794

HEWITT, Mischa a TELFER, Kevin. Earthships: building a zero carbon future for homes. BREPress, 2007. ISBN: 978-1-86081-972-8.

ÇENGEL, Yunus A. Heat Transfer: A Practical Approach. 2rd ed. Boston: WCB/McGraw-Hill, 2002. ISBN 978-0072458930.

Deadline for submission Bachelor's Thesis is given by the Schedule of the Academic year 2020/21

In Brno,

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ABSTRACT

The present thesis describes the Earthship concept as a self-sufficient, sustainable solar passive house and provides a detailed description of energy systems in the Earthship. The thesis also seeks to determine the energy potential of the Earthship concept by estimating the dwelling's energy balance. A complete overview of the Earthship ideology and a detailed description of its energy systems, which introduce the topic to the reader, were researched in publications and compiled in this thesis. The energy performance of such housing was evaluated according to the Czech and European standards by calculating heat gains and losses in a chosen Earthship study model. Consequently, the passive house criteria were analyzed. The advantages and disadvantages of the concept were critically discussed based on the research and the energy balance estimation. Performance evaluation of the chosen Earthship model shows that the dwelling does not fulfill the passive house criteria; however, it is still a low-energy house. The conducted research shows that the design is highly dependant on the climate and the season; therefore, it might not function everywhere in the world.

KEYWORDS
Earthship, passive house, energy balance, heat losses, heat gains, tire walls, energy efficient house, autonomous house, sustainable housing.

ABSTRAKT

Táto práca popisuje koncept Zemelode ako sebestačný, udržateľný solárny pasívny dom a taktiež poskytuje podrobný opis energetických systémov v Zemelodi. Práca sa tiež snaží určiť energetický potenciál konceptu Zemelode pomocou odhadu energetickej bilancie daného obydlia. Celkový prehľad ideológie Zemelode a detailný opis energetický systémov, ktoré predstavujú tému čitateľovi, boli získané z publikácii rešeršom. Energetický výkon tejto stavby bol vyhodnotený podľa českých a európskych noriem pomocou výpočtu tepelných ziskov a strát pre zvolený model Zemelode. Následne, boli skontrolované kritéria pasívneho domu. Výhody a nevýhody tohto konceptu boli kriticky zhodnotené na základe rešeršu a výpočtu energetickej bilancie. Zhodnotenie výkonu zvoleného modelu Zemelode ukazuje, že toto obydlie nesplĺňa požiadavky pasívneho domu, avšak stále sa jedná o nízko-energetický dom. Vykonaný rešerš ukazuje, že tento dizajn je vysoko závislý od podnebia a ročného obdobia, preto nemusí fungovať všade vo svete.

KĽÚČOVÉ SLOVÁ
Zemeloď, pasívny dom, energetická bilancia, tepelné straty, tepelné zisky, steny z pneumatík, energeticky efektívny dom, autonómny dom, udržateľné bývanie.

BIBLIOGRAPHIC CITATION

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I, the undersigned, hereby declare that I wrote this bachelor's thesis by myself under the supervision of Ing. Tomáš Mauder, Ph.D. All sources have been accurately reported and acknowledged, and they are listed in references. I hereby give consent for my thesis, if accepted, to be available for photocopying and understand that any reference to or from my thesis will receive anacknowledgment.

Michaela Mária Peciarová

I would like to express my deepest gratitude to my supervisor Ing. Tomáš Mauder, Ph.D., for his helpful guidance, insightful comments, and considerable encouragement to finish this thesis.

Michaela Mária Peciarová

Contents

Introduction

The evolution of humankind has brought many inventions and discoveries that make our lives better in every possible way. However, great ideas go hand in hand with even more significant issues. People nowadays face an enormous problem that no other generation had to deal with before – climate change. Producing waste in large amounts is one of the most significant contributions to destroying the environment, and it is a bi-product of human life on the planet.

Successful reduction of greenhouse gases and helping nature recover means an improvement in waste and disposal management. As much as individual behavior plays a vital role in improving climate, a radical change in the environment could be achieved by large industries reducing and recycling their waste. The construction industry is one of the most wasteful industries that could be more eco-friendly, embracing a new building concept.

Additionally, the growth of the population has resulted in a need for more housing units. To provide as many as possible, humans have become dependent on centralized energy systems. Heating and cooling networks are entirely dependent on these centralized energy systems, and most housing units nowadays would be non-functional, regarding comfort, without them [1]. The construction industry is having difficulties to keep up with population growth; ergo, it does not appropriately manage its waste. There is a reason to believe that a building design, functioning on clean energy, and using resources efficiently is needed for the population to grow.

Earthship was introduced in the 1970s by Michael E. Reynolds, an architect, who trademarked the design. Articles about trash and unaffordable housing inspired Michael Reynolds to build his first trash can wall that started Earthship's idea. In his book, he said, "We need to evolve self-sufficient living units that are their own systems. These units must energize themselves, heat and cool themselves, grow food, and deal with their own waste" [1]. The architect believes that people need to learn to live without centralized energy systems. It will decline the destruction of the planet and possibly reverse some deterioration aspects.

Earthship is an off-grid, independent vessel that aims to be the future of society's habitat on this planet. Using recyclable and natural materials while providing ecological living conditions for society is an advantage of this type of housing. Despite not knowing what the future holds, there are two main aspects of housing to be considered – the availability to the masses and affordability. Since Earthship is made out of garbage and natural materials mostly, it could be made affordable and non-exclusive. Therefore, this independent vessel is a candidate for the sustainable living of ordinary people.

1 Background

1.1 Earth sheltering

“Earthships must be built out of Earth on stable, undisturbed Earth. The design is not meant to resist the Earth but to join it” [1]. Using Earth as a thermal mass is an old, traditional practice that dates back in time, as shown in figure 1.1, which shows a turf house in Iceland from the 1970s. Earth as a thermal mass can provide excellent insulation since it adapts to the weather and withstands weather conditions, unlike other materials [2]. When the outside temperature rises and the Earth is warmed up, the heat is slowly transferred to the house walls, following indoors, creating a warm inside temperature. After the outside temperature drops, the house walls start to get colder, resulting in releasing more heat to the inside of the building. This process is an application of the second law of thermodynamics, which states the total entropy of a system and its surrounding will never decrease, consequently the heat will always travel from hot to cold [3]. When figure 1.1 was taken, the outside temperature was – 4 °C, and the wind speed was approx. 24 km/h, which according to the Beaufort scale, is a moderate breeze. The turf house’s temperature was 8 °C – 9 °C, which makes it approx. 12 °C difference. The Earthship benefits from using Earth as one of its building materials as the turf houses did back in the days [1].

Figure 1.1: Turf house from 1970 in Hjarðarhaga, Iceland

1.2 Earthships around the world

The demand for Earthships has been growing over the years. According to Reynolds, there around 2000 Earthships around the globe [4]. It would be of particular interest to look at the different Earthships built in America, Europe, Africa, Asia, and Australia.

The first Earthship that was ever built is in Taos, New Mexico. Michael Reynolds built it in 1979 [1]. Since then, more Earthships had been constructed in New Mexico, creating an Earthship community called The Greater World Earthship Community, shown in figure 1.2. It is the world’s largest off-grid subdivision with 79 home sites [5]. Except for the Earthship com-

Figure 1.2: The Greater World Earthship Community [6]

munity in New Mexico, there are Earthships built in Canada, Colorado, Florida, Belize, Puerto Rico, Haiti, and other North American parts. Moving onto South America, the first sustainable school[1] in Latin America was built in 2016 in Uruguay [7]. This school is an Earthship, and Michael Reynolds designed it. European builds, shown in figure 1.4, are primarily located in Spain, France, and the UK. However, some Earthships are situated in Sweden, Belgium, Netherlands, Denmark, and the Czech republic. An interesting fact about the European Earthships built in Belgium and the UK is that these projects had faced difficulties getting permission to use tires for construction [8]. The first school ever to use the Earthship's concept was built in Sierra Leone in 2011. Other African Earthships are in South Africa, Malawi, and Swaziland. Australia also has a fair share of Earthships, of which some serve as rental accommodation. Asia has the least amount of Earthships but the most recent Earthship was built in Japan in November 2020. The figure 1.3 shows the Earthships situated on different continents.

Figure 1.3: The Grand Central Network of Earthships [9]

The Earthship concept does not necessarily have to be a housing concept only. Earthships can also be guesthouses or other types of rental accommodation. In fact, Michael Reynolds and his team planned to build an Earthship Island in Indonesia for vacation purposes [11]. Up to

[1] more information at `https://www.youtube.com/watch?v=5hbJylFaufk`

Figure 1.4: Overview of Earthships in Europe [10]

now, no studies have reported the completion of the Earthship Island Indonesia project. The table 1.1 compares prices of different Earthships available for renting. Such bookings can be made via Airbnb or Tripadvisor, and the guest receives instructions on how to sail the Earthship. Most of these accommodations are booked out for six months in advance and have great reviews.

Table 1.1: Comparison of rental prices of different Earthships

Name of the Earthship	Location	No. of bedrooms	Price per night €
Ironbank	Australia	1	212
Tiny Bunkhouse	New Mexico	1	54.68
Patagonia Eco	Argentina	1	36.90
Caliu Earthship Hotel	Uruguay	1	127
Studio Earthship	New Mexico	2	118
Eco House	France	2	90
Owls Nest	Guatemala	2	105
Casa Muntasal	Spain	3	60

* Prices obtained from `www.airbnb.com` and `www.tripadvisor.com`.

Having discussed the existing Earthships worldwide, it can be assumed that there is more than one use of this type of vessel. The projects mentioned in this section show that even tourist accommodation or schools can be sustainable using the Earthship architecture. To develop a complete picture of all the Earthships built globally, additional studies will be needed to monitor the dwellings' growing numbers.

2 Design principles and features

All creatures live interfacing with nature except humans, who instead are responsible for polluting the environment every day. Designing the Earthship is based on understanding its purpose. A self-sufficient off-grid dwelling behaves as a power plant, water and septic tank, and heats and cools itself and produces food [1]. The design principles and features of the Earthship are listed below, however, some of them are discussed in separate chapters.

The defining principles:

- comfort for people
- site harmony
- sustainable resource use
- autonomy and selfsufficiency

The main design features:

- low impact materials
- passive solar design
- renewable energy
- rainwater harvesting
- using plants to treat wastewater
- food production

2.1 Site selection

Most individuals consider affordability and proximity to a particular area when choosing a location for their home [12] . However, the location has everything to do with building an autonomous vessel that interacts with natural phenomena and uses natural resources. Earthship requires sun, earth, water, and wind. Therefore, most Earthships are built off-grid, and some of them are located in the suburbs [1].

For the Earthship to use solar energy, it has to encounter it, meaning the orientation of the window glazing has to be towards the south. Hence, the other side of the Earthship has to face the north to get better insulation from the ground. This positioning applies to the northern hemisphere, vice versa for the southern hemisphere [1]. Figure 2.1 shows the Sun's positioning during the winter and summer months, from which it is clear that the Sun is never on the northern side of the vessel. An equally significant aspect of the positioning of the Sun is the amount of sunlight per day. Regarding the sunlight, it may be argued that the Earthship is not suitable for all climates.

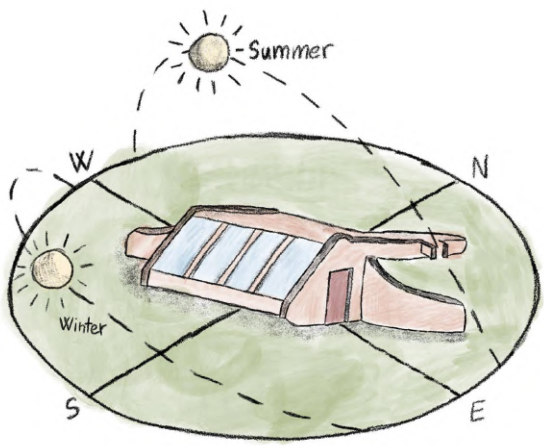


Figure 2.1: Sun's positioning during seasons in northern hemisphere. Redrawn from [12]

As the name of the vessel suggests, the Earthship relies heavily on the Earth itself. Since the Earth is diverse regarding climate, topography, soil stability, and other natural phenomena, choosing an Earthship location is crucial [12]. An autonomous vessel requires a south-facing slope, so the topography of the land needs to be considered. Moreover, being self-sufficient means growing food for the inhabitants of the house. Plants require fertile, stable soil to grow, and living on stable soil means lower risks of damage by natural disasters such as flooding or mud sliding [1].

"The Earthship must both avoid and encounter the water to provide human habitat" [1]. The vessel is heavily dependent on harvesting rainwater with many uses, from supplying the appliances to watering the plants. Thus, it has to be built off the grid to collect as much rainwater as possible. Off-grid locations offer natural drainage patterns where the water runs downhill [2]. However, having water running down to the house from all directions is not the best solution either. The preferable situation is to have less runoff [2] and channeling it around the Earthship. Such a location is the peak of a hill where there is no runoff from higher places [1]. Having access to a spring or a well on the Earthship's ground is an advantage since rainwater might not be available all the time. Wet sites and flood-risk sites must be avoided.

Hot air is less dense than cold air; therefore, the Earthship has a lower window and a higher window in each room to regulate the airflow. To take advantage of the wind for ventilation, the Earthship needs to be situated away from the prevailing wind [3] [1]. This way, the wind enters the lower window and carries the air out through the higher window, resulting in pleasant indoor temperature and fresh air, as shown in figure 2.2. Moreover, wind power can be a source of electricity using a windmill, described in section 3.2.

To summarize, the most suitable location for an Earthship is a climate with much sunlight and preferably on the peak of a hill, definitely not a valley.

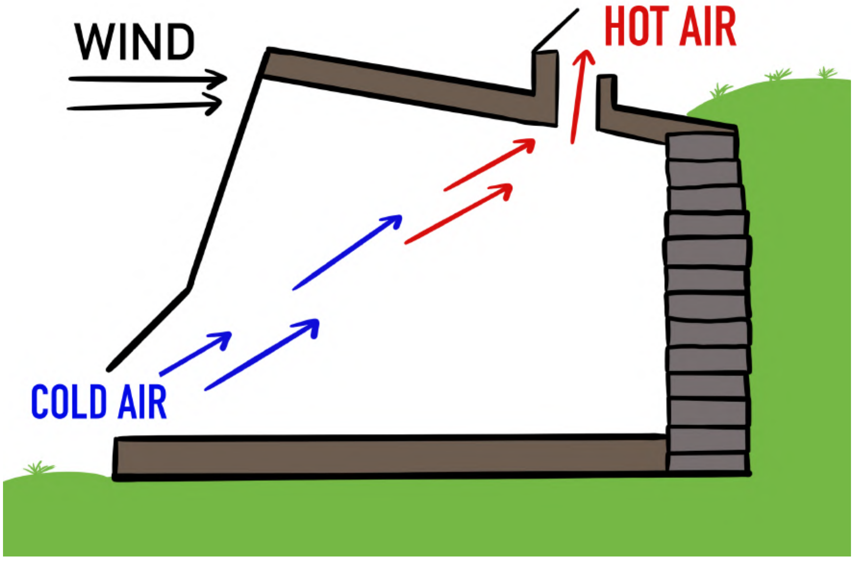


Figure 2.2: Ventilation using wind. Redrawn from [1]

[2]the unabsorbed rainwater running downhill
[3]a wind from the direction that is predominant or most usual at a particular place or season

2.2 Passive solar design

The purpose of the Earthship is to reduce its demand for energy before using methods to obtain energy from renewable sources. The passive solar design is not a new technique, and it dates back to the indigenous Americans [8]. The solar design goal is to capture the heat from the sun within the building elements and release it when the sun is not shining. This way, the Earthship can heat and cool itself [5].

There are two approaches to passive solar systems – direct gain and indirect gain. Direct gain from the sun can be achieved by having thermal mass floors and walls in the Earthship. The radiant heat enters the Earthship through south-facing windows, and it is directly admitted to the walls and floors. During the night, the heat is released from the thermal mass floors and walls, heating the interior space [5]. The indirect gain approach is suitable for Earthships where the thermal mass, is the Trombe wall [4] and is located right behind the south-facing glass, shown in figure 2.3. The Trombe wall has vents on the top and the bottom. The hot air rises through the vents on top, and the cold air is drawn through the vents at the base of the wall. During the night, the vents are closed to control the heat convection [8]. Both methods of passive solar gain require thermal mass walls to store the heat and release it later. Figure 2.4 shows the solar gain during the day and the heat release during the night.

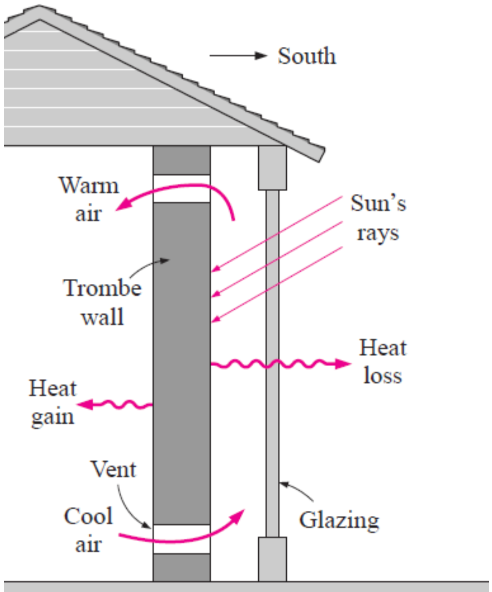


Figure 2.3: Trombe wall [3]

When the sun is higher in the sky during the summer months, the Earthship absorbs less heat, resulting in pleasant indoor temperature [8]. In case the temperature inside is too high, there is a natural cooling system in the Earthship, described in figure 2.2.

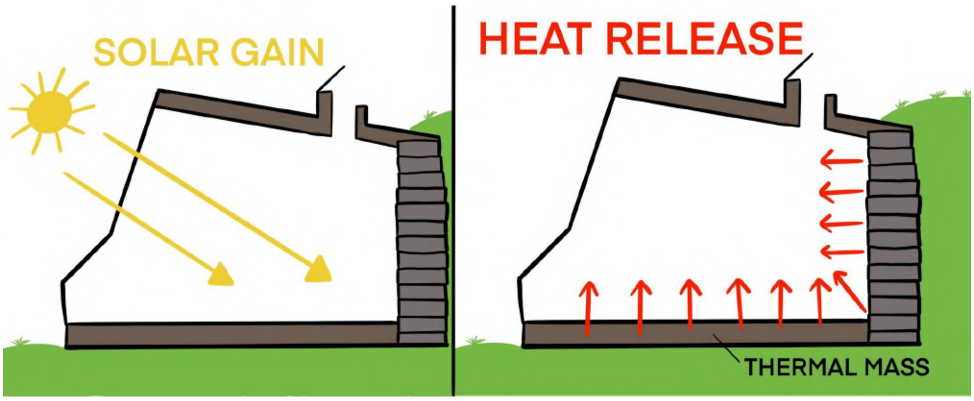


Figure 2.4: Passive solar design. Redrawn from [8]

[4]dark painted thick masonry wall used to absorb solar energy in passive homes

2.3 Low-impact materials

To live as sustainably as possible means using what people already have to the best of their abilities, including their homes. When choosing sustainable building materials, the first factor to consider is the material's thermal properties – the better the thermal properties of a material, the less energy it takes to run the house [12]. Using such materials results in lower consumption of energy and less air-polluting while burning fuel. Good insulation must be used to achieve the energy efficiency of the house. The purpose of insulative material is to slow down the heat transfer.

Fourier's law of heat condutction, equation (2.1), shows that the higher the thickness of a material, the lower the heat transfer.

$$\dot{Q} = -\lambda S \frac{\triangle T}{\triangle x} \qquad [\mathrm{W}] \qquad (2.1)$$

where:
$\dot{Q}$ heat flow rate $[W]$
$\triangle T$ temperature difference $[K]$
$\triangle x$ thickness of the material conducting heat $[m]$
S the cross-sectional area of the material conducting heat $[m^2]$
λ the thermal conductivity of a material $\left[\frac{W}{m \cdot K}\right]$

The thermal resistance of a material predicts the effectiveness of the insulation. Equation (2.2) shows that the thicker the material, the higher the value of thermal resistance. This means that a thicker material has lower heat transfer. The denser the material, the thicker the insulation. Therefore, a dense, heavy material provides better insulation and keeps the inside temperature stable, making the Earthship behave like a thermal storage. Such materials are usually made of mineral wool, fiberglass, polyethylene, foam, or calcium silicate [3].

$$R = \frac{\triangle x}{\lambda} \qquad \left[\frac{m^2 \cdot K}{W}\right] \qquad (2.2)$$

The second factor to consider is the durability and resilience of a material. Ideally, the material's durability should be a property rather than using harmful chemicals to achieve it [1]. The Earthship must also withstand any shaking caused by earthquakes or wind, which means that the building material needs to have the capacity to move. Brittle materials, such as concrete, do not withstand any movement because they crack and fracture. On the other hand, rubbery materials can withstand movement, making them (according to Reynolds) more suitable for construction [1] [2].

In addition to these properties of a material, its origin must be considered [12]. As mentioned in the previous chapter, construction is one of the most wasteful industries. According to the Eurostat[5], the construction industry produced 38 % of waste in 2018, considering 28 EU countries, shown in figure 2.5 [13]. It is the highest percentage of waste by economic activity. It can be concluded that a reasonable amount of materials bought to be used in construction ends up thrown away and never used again. Therefore, using products or materials that have been recycled, repurposed from a non-virgin resource, or products that serve more purposes, saves further depletion of the natural resources. Not only do most of the materials need to be recycled and natural, but they also need to be indigenous [12]. Depending on where the Earthship

[5]European Statistical Office

is built, the ideal materials used in it would be indigenous because they have lower embodied energies from transportation. Building an Earthship should be a low-impact procedure, and it takes less energy to use materials locally available rather than shipping them across the world [1]. When it comes to the energy used for shipping, the materials' manufacturing energy must be considered too. The manufacturing of the materials needs to use less energy or almost no energy to have a small impact on the environment if building many Earthships [1].

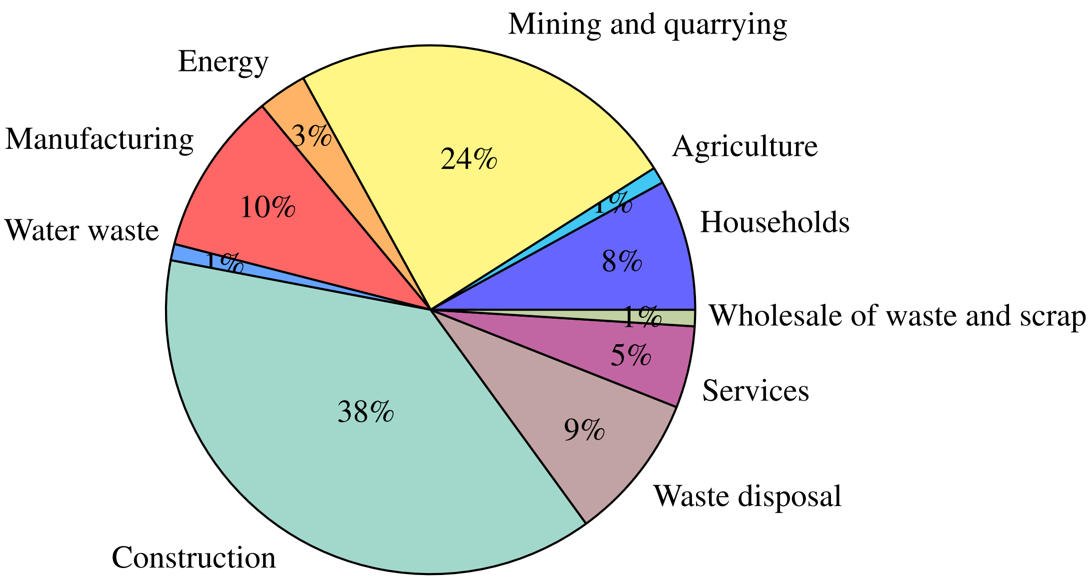


Figure 2.5: Waste by economic activity [13]

Application of average human capabilities needs to guide the green home building process since the Earthship is available to everyone of any occupation and any skill set. There should be no need for high technology applications. Necessary human skills are enough to assemble the building blocks of an Earthship [1] [2]. In conclusion, there is a lot to consider and research before choosing the materials for building an Earthship. Some materials do not follow all the principles mentioned before, but they are still used in the Earthship construction. There are two main categories of materials – primary and secondary materials [1].

2.4 Primary and secondary materials

The primary building block provides the main structure and determines the performance of the Earthship. Since the primary building block is used for the Earthship's main structure, it needs to follow all the materials' design principles. Based on Michael Reynolds' research throughout the years, it has been established that the most suitable building material for the primary structure of the Earthship is a rubber automobile tire rammed with packed earth, shown in figure 2.6 [1]. Considering the rubber tire's indigeneity, it can be said that tires are indigenous to every populated area all over the planet. Everyone has access to tires, whether old or new, without the need for shipping them across the world. Tires can be gathered without any special skills or technology, making them easy to build with. The rubber tires already provide a form for a building block rammed with pack earth found anywhere [1]. The rubber itself makes an excellent thermal mass, and adding the earth to it, makes it even denser and more efficient. Since the tires have a large diameter, the Earthship walls are thick, providing a decent thermal insulation [1].

Figure 2.6: Tire wall [14]

Secondary materials are materials used to fill in walls, ceilings, floors, glazing, and carpentry [1]. The design principles should also apply to these materials. The most significant secondary material is the aluminum beverage can, which is used for wall filling. The aluminum cans meet all the criteria except for the thermal mass; however, this property is unnecessary for the wall filling [1]. Since many beverages are sold in aluminum cans, they can be found anywhere globally, making them indigenous. Using aluminum cans as wall fillers reduces waste since they would have ended up thrown away. Glass bottles are used to fill in walls too, as shown in figure 2.7. Other secondary materials occurring in the Earthship are wood, concrete, glass, or steel, depending on what is available at the Earthship location [1]. Wood is mostly used for ceiling decks; however, concrete or steel beams can be used. Floors are made of concrete, but there are mud floors in some Earthships. Glass is used for the southern glazing, which should be double-pane to collect as much heat from the sun as needed.

There are principles to follow when choosing these materials, but there is no strict set of rules. It is all about using what is available and trying to use it in a most efficient way. There are no boundaries to peoples' imagination and creativity as long as the Earthship's idea is followed. The construction industry would change rapidly if it started to follow some of these principles.

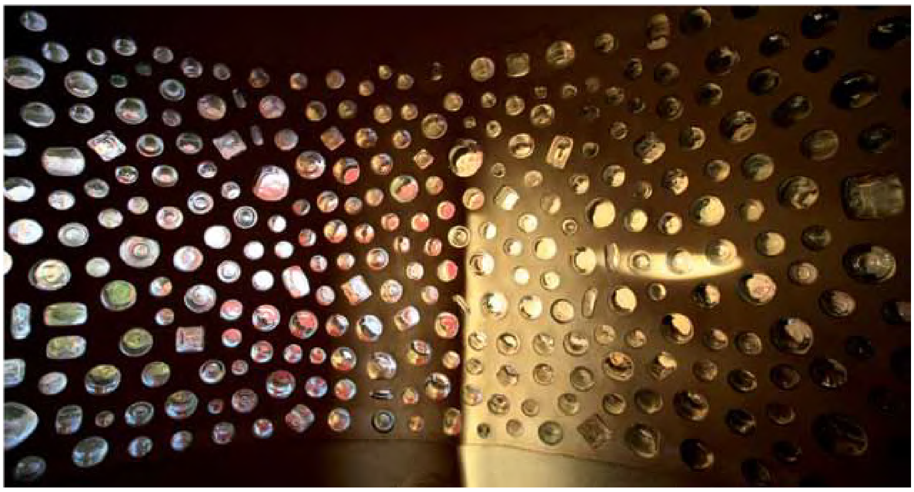


Figure 2.7: Wall filled with glass bottles [8]

2.5 Modular approach

Building and assembling the Earthship is based on a modular approach. There are two main types of modules: the U-module, being more popular, and the hut module. As the name suggests, the U-module has a shape of U, and the hut model has a round shape. The module itself is an individual room with three main walls and an entrance. The sizing of the modules is entirely up to the inhabitants of the house. Modules can be partially submerged into the ground, as shown in figure 2.2, and they can be combined in different ways to create a house, established in figure 2.8. However, there are specific methods for connecting the modules; since a module cannot be expanded to create a house, it can only be multiplied and combined. These methods are meant to maximize solar gain during winter [1].

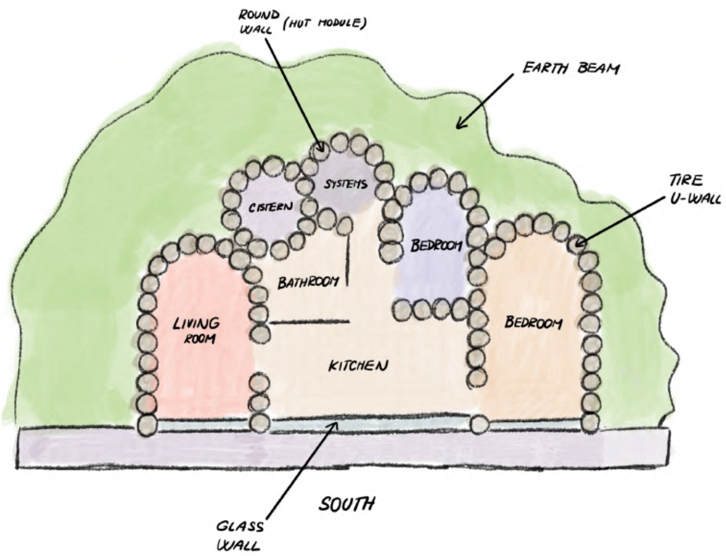


Figure 2.8: Possible arrangement of the U and hut module. Redrawn from [15]

The first type of arrangement is called the Straight row, shown in figure 2.9. Sharing a common wall, the modules can be put next to each other in a straight row, having the same orientation towards the sun. Instead of each room having a small greenhouse, there is one big greenhouse that becomes a hallway. The greenhouse can be closed off from some rooms while remaining open to others. This arrangement creates a heat duct since the sunlight is collected through the glass wall, and the heat can circulate through the individual rooms. The simplicity of these modules' arrangement ensures an excellent solar performance of the Earthship, and it can be easily preserved [1].

The second type of arrangement is called the Staggered row, relating to the Azimuth angle[6], shown in figure 2.9. The modules are stepped back from one another without causing shadows, having a connecting glass. As in the previous arrangement, the greenhouse becomes a hallway and acts as a heating duct. The modules can be stepped back as far as the azimuth angle allows them. The angle is determined by the winter sun's location between 10:00 and 14:00 because the sun is the most effective in heating between these hours. The spaces created by stepping the modules back can be filled with thermal mass for better insulation [1].

The third type of arrangement is called the Straight step – on a slope shown in figure 2.10. The modules can be leveled by placing one module behind and above another, step-like. Since

[6]an angular measurement of direction from which the sunlight is coming

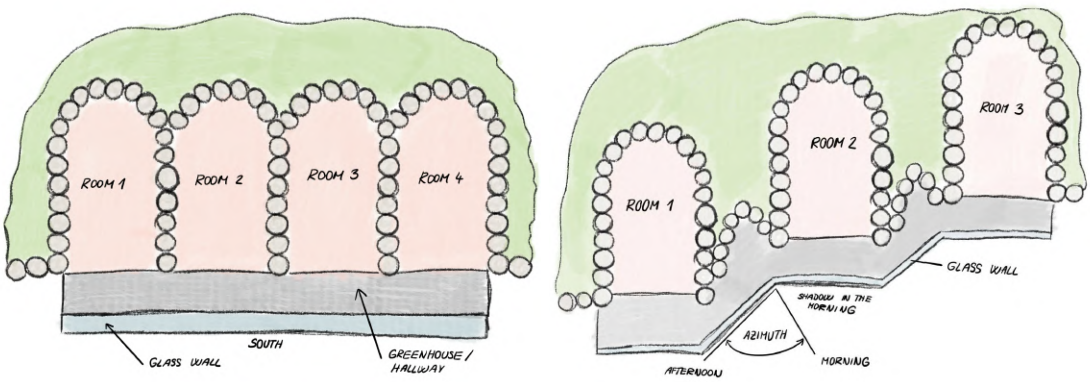


Figure 2.9: Straight row and Staggered row. Redrawn from [1]

this kind of arrangement is step-like, it is necessary to have a sloping site. Straight step arrangement allows more modules to be combined in a row as well as in steps. Previously mentioned arrangements can be used for the row combination. There can be a space where the steps overlap, which can be used for growing fruit or nut trees [1].

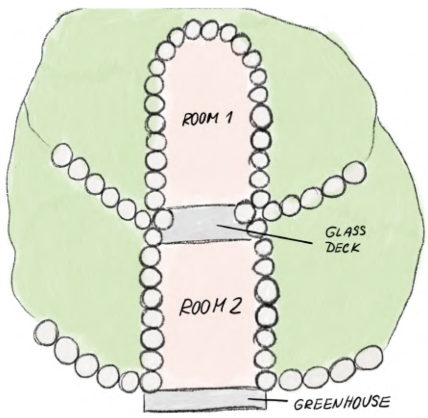


Figure 2.10: Straight step – on a slope. Redrawn from [1]

These different arrangements can be combined. However, some combinations are not recommended. Such a combination would be two modules placed behind one another on a flat site, creating no sunlight entry. Also, building two modules on top of each other is not recommended unless an expert had been consulted [1].

2.6 Food production

It is important to note that food production all year round is a significant attraction of Earthship dwellers and builders. Reynolds claims that the ability to stagger crops and harvest a little at a time is a luxury available to the Earthship owners [1]. According to the Earthship concept, the dwelling owners can grow almost anything inside of much better quality than store produce. However, serious food production requires the use of Lascolite[7] instead of conventional glass.

The food plants are planted in the botanical cells in the conservatory. The plants gather nutrients from the greywater passing through the botanical cells. The issue of having a conservatory inside the vessel is the presence of insects or even mice. Yet, Reynolds describes a

[7]a fiber glass

solution for this problem in his book [1]. The only successful food production example so far is the Phoenix Earthship in New Mexico [8]. It has a large-scale greenhouse which allows a large food production. Some Earthship inhabitants even keep chicken coops for eggs in their backyard, as in the Earthship project in the Czech republic.

Even the idea of catching fish from a pond inside of the Earthship had been demonstrated in the Phoenix Earthship [16]. It is crucial to bear in mind that the fish had to be caught and brought into the Earthship's ecosystem, and this action itself has a significant environmental impact [17]. To provide fish for the dwelling inhabitants all year round, the fish would have to breed and grow at enormous rate, which is impossible since commonly eaten fish takes 2-5 years to grow into an adult size [18].

Small amounts of food can be produced in almost any Earthship. However, the smaller the greenhouse, the less food supply. Due to lack of space in the Earthship and the climate conditions, meaningful self-sufficiency can be neglected in terms of the food amount produced.

3 Renewable energy systems

As a ship sails on the water using renewable natural resources such as wind, tide, and currents, the Earthship sails on the Earth, encountering natural phenomena and using raw materials, hence the name [1]. In the light of carbon capture, it can be argued that energy systems play a vital role in the sustainability of a house. To lead an energy-conscious life means to reduce the electrical requirements of the house via its design [19]. Therefore, this chapter will explore the renewable energy usage in the Earthship.

3.1 Solar energy

The strategy to maximize the solar energy intake is described in chapter 2, which provides information on choosing the best location for the Earthship and on the passive solar design. This chapter aims to provide an understanding of the nature of solar power, how to collect and store solar energy, and how to live with it. Sunlight is a radiation of a specific wavelength, and it consists of visible light, UV radiation, and infrared radiation. When the sunlight meets a material, all of this radiation is either absorbed, transmitted or reflected [3]. The absorbed radiation is turned into heat. This nature of the sun's energy provides three main usages of solar energy – solar thermal energy, solar electric power, and biomass. Solar thermal energy is discussed in chapter 4.

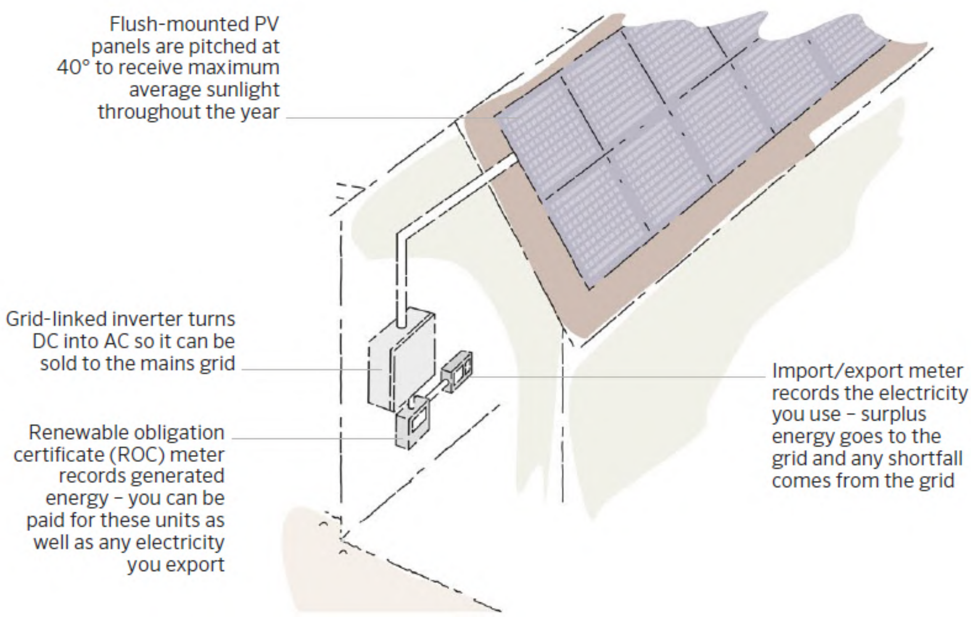


Figure 3.1: Photovoltaic system [2]

A complex way of harnessing the sun's energy is using photovoltaic technology, shown in figure 3.1. This technology captures photons from the sun's rays and instantly converts them to direct current using solar panels. Both direct and indirect sunshine can be used for power [2]. The solar panels produce no pollution, and they require little maintenance, making them more available to the masses. These solar panels are made of cells from semiconductor materials such as silicon, which has free outer electrons around the atom. After the photons hit the first layer of silicon, they flow to the layer beneath that contains atoms with no electrons missing. This flow through the cell creates a small current, but with so many cells linked together, it makes a usable voltage of direct current electricity. Direct current is changed into alternating current via an inverter [2]. This electricity is used for the appliances in the Earthship. As the Earthship's idea is to eliminate the need for electricity, there is a need to consider the importance of devices to be used in the Earthship [19]. Using solar power for electricity is again dependant on the location of the Earthship and the amount of sunlight per day; therefore, a backup supply of electricity might be needed for inexperienced solar energy users, such as wind power described in section 3.2.

Lastly, biomass is an energy that has been collected and converted from the sunlight by the plants. There are two groups of biomass: woody and non-woody. Woody biomass, as the name suggests, is wood used as a fuel. Non-woody biomass includes animal waste, high-energy crops, and biodegradable by-products of food production [2]. Wood is the most common type of biomass for domestic usage; however, there is a debate about this fuel's environmental impact [8]. Even though trees and plants capture CO_2, burning wood produces CO_2 as well, which is not absorbed immediately but over a long time. As long as biomass combustion does not exceed the natural production of carbon dioxide, this type of fuel can be considered sustainable.[2] There is also a possibility of purposely growing energy crops and trees, but there is an issue of reducing available land for food production. The Earthship can benefit from using biomass as a fuel for specific types of boilers or burning wood in a fireplace [19]. Only three Earthships in Europe use biomass, located in the UK, Spain, and France [8]. Nonetheless, biomass is a renewable energy source that can be used effectively in an Earthship on a small scale.

3.2 Wind energy

As the sun warms the Earth's atmosphere unevenly, the air flows from one place to another, creating a moving mass called wind. Harnessing wind power is one of the most common and most cost-effective ways of using renewable energy sources [20]. Since wind power is heavily dependent on wind speed and turbulence, it is rather an additional electricity supply in the Earthship.

The higher the difference between atmospheric pressures, the stronger and the faster the wind. Equation (3.1) shows that the higher the wind speed, the higher the kinetic energy [20].

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \qquad [J] \qquad (3.1)$$

where:
m mass $[kg]$
v velocity $[\frac{m}{s}]$
Wind power can be calculated using equation (3.2). Since power is energy per second, it is calculated using mass flow rate instead of mass [20].

$$P = \frac{E_K}{t} = \frac{1}{2} \cdot \dot{m} \cdot v^2 \qquad [W] \qquad (3.2)$$

where:
$\dot{m}$ mass flow $\left[\frac{kg}{s}\right]$
t time $[s]$
The wind power is a function of wind velocity, air density and the size of the area the wind is flowing through. Therefore, the wind power can be calculated using equation (3.3), which shows that a wind turbine's power output is proportional to wind speed cubed [20].

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot v \cdot v^2 = \frac{1}{2} \cdot \rho \cdot S \cdot v^3 \qquad [W] \quad (3.3)$$

where:
ρ the air density $\left[\frac{kg}{m^3}\right]$
S the area perpendicular to the airflow $[m^2]$

Depending on the average speed of wind in the Earthship's location, it is easy to calculate approximately how much power the turbine will provide for the dwelling [2] . Earthship being an off-grid vessel results in lower wind turbulence, as there are no surrounding buildings or objects that would remove energy from the wind [19]. Low wind turbulence is the key to having a decent electrical output from the turbine [20].

The approximate value of wind power generated by a wind turbine built off-grid can be calculated using data from table 3.1 and properties of air. Since the air density depends on the Earth's atmosphere and the outside temperature, the power output calculated in the table 3.1 is approximated to certain conditions. However, the table shows that unless the Earthship is built off-grid on an open site, the wind turbine's power output will be quite low [8].

Nevertheless, some European Earthships do have a wind turbine as a back-up supply of power [8]. This chapter showed that having a wind turbine on the Earthship's site as an additional power source is helpful.

Table 3.1: Average wind speed in different site conditions and power output per 1 m^2 at atmospheric pressure and 20 °C [21] [20]

Site conditions	Average wind speed $\left[\frac{m}{s}\right]$	Power output $\left[\frac{W}{m^2}\right]$
Trees and buildings	3	16.2
Open fields with few hedges	4.5	54.7
Hilltops or coasts (open sites)	6	129.6

3.3 Hydropower

Acquiring energy from water is one of the most ecological ways of energy production. In 2019, wind and hydropower accounted for 70 % of the total electricity generated from renewable resources in the European Union, shown in figure 3.2 [22]. Even though harnessing water energy is not incorporated in the Earthship's original trademarked design, this chapter is set out to examine the onsite possibility of hydroelectric power.

Suppose the Earthship is built on a land where a steady flowing water body is present, and the water body is permitted to be diverted for power purposes. In that case, the vessel can use electricity from this source [2]. Since flowing water can generate electricity by spinning a water turbine's rotor connected to an electromagnetic generator that produces electricity, essential measurements need to be carried out before building a small hydroelectric power plant[8] [20]. Crucial parameters affecting the power plant are the flow of the stream and the head which is the vertical distance from the place of capture to the location of use. These parameters determine everything about the hydroelectric system – from water diversion pipeline size, turbine type to the generator size [2]. The power of a small hydroelectric power plant can be calculated

[8]a power plant generating power with magnitude of less than 10 MW

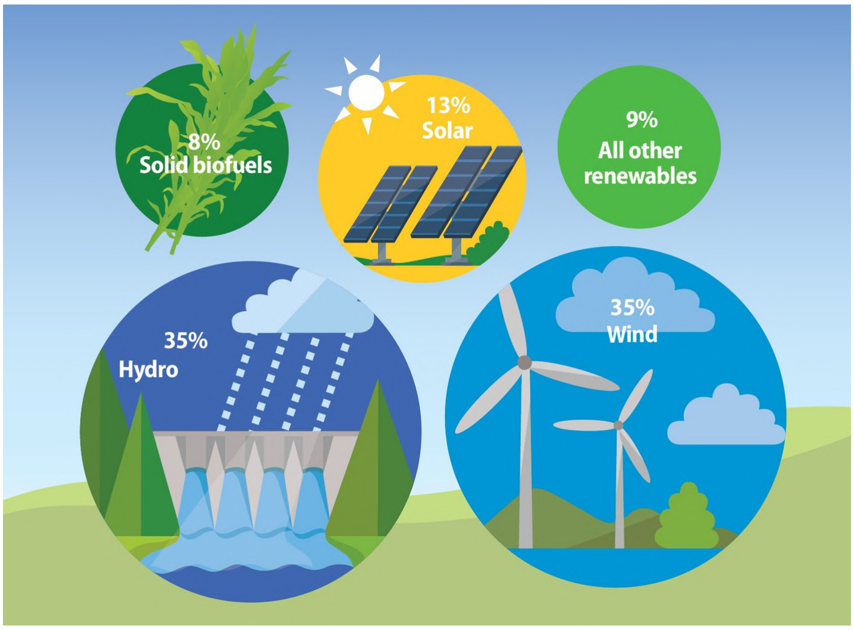


Figure 3.2: Renewable sources generating electricity in EU, 2019 [22]

using a simplified equation (3.4). The power output, calculated using equation (3.4), does not account for the hydroelectric system's losses caused by the friction of the water moving through pipelines and turbine or the drive system's energy loss. The real power output will be lower, and it can be calculated using equation (3.5). The efficiency of the hydroelectric system depends mostly on the design of the turbine [12] [21].

$$P = Q \cdot g \cdot H \qquad [W] \quad (3.4)$$

where:
Q the flow of the stream $[\frac{m^3}{s}]$
H the head $[m]$
g the acceleration due to gravity $[\frac{m}{s^2}]$

$$P = \eta \cdot Q \cdot g \cdot H \qquad [W] \quad (3.5)$$

where:
η the efficiency of the system $[-]$

There are two main types of turbines: reaction and impulse turbines. The reaction turbines, such as Francis and Kaplan, are used on low-head and high-flow sites [2]. The impulse turbines, such as Pelton and Turgo, are typically used on high-head sites, and they operate in the air using high–velocity jets of water. The choice of water turbine is affected by the Earthship's site, and the water turbine affects the power provided by the hydroelectric system [20].

Another way of harnessing energy from water is by building a watermill. The principle of acquiring hydropower from the watermill is long-established and straightforward. The water flow pushes the wheel around, the water is captured in angled buckets and then poured back into the water body. These revolutions of the wheel are converted into electricity. There are different water wheel types depending on the water source, making this type of hydropower available to diverse landscapes. The watermill's efficiency depends on the proper choice of the water wheel for a given terrain. The water wheel's power output can also be calculated using equations (3.4) and (3.5) [2].

The purpose of this chapter was to examine the onsite possibility of hydropower for the Earthship. In conclusion, if there is a water body present on the Earthship's site, then acquiring energy from water is efficient and ecological. Ensuring appropriate hydropower systems for the Earthship should be a priority for the Earthship's inhabitants in the presence of the onsite water body since it is the most stable power source.

3.4 Geothermal energy

The thermal energy generated and stored in the Earth is called geothermal energy. It can be used for heating or generating electrical energy. The total geothermal power output of the Earth is equal to 40 000 GW, approximately four times the total power consumption on Earth [20]. The most significant advantage of geothermal energy is that it is not affected by weather conditions and it has low emissions. However, using geothermal energy is highly dependant on the location. Geothermal energy is usually present in areas with volcanic activity or near the boundaries of tectonic plates. Figure 3.3 shows suitable locations for the use of geothermal energy. This form of energy can benefit the Earthship's design, especially in colder climates where sunlight is absent for long periods of time. Therefore this chapter will focus on powering the Earthship with geothermal energy.

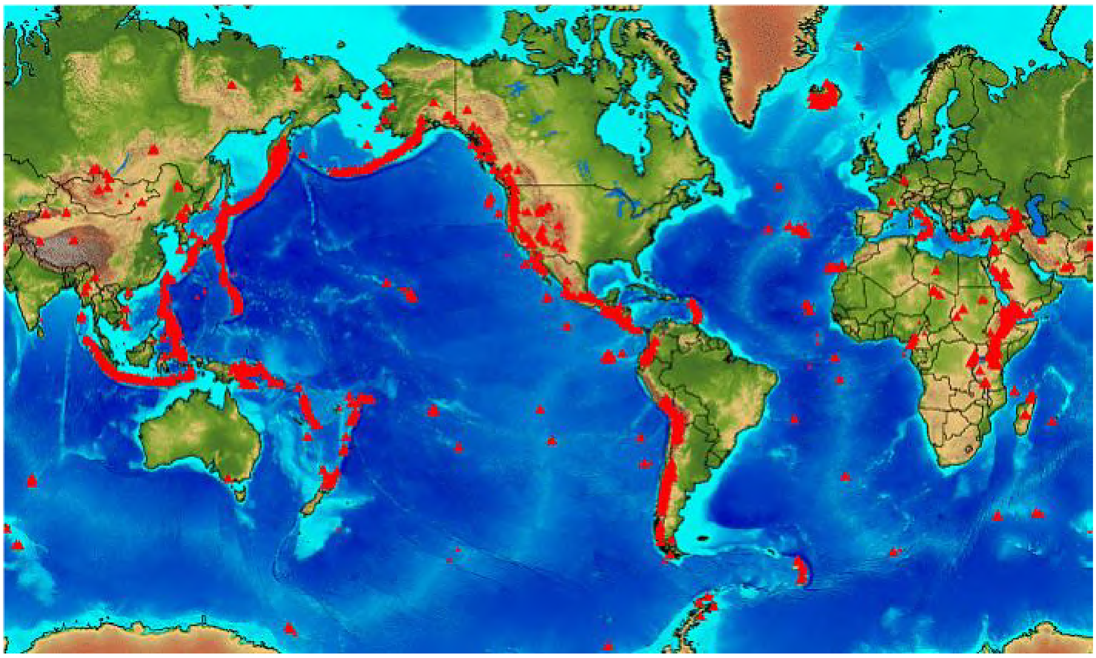


Figure 3.3: Tectonic map of the world and areas suitable for using geothermal energy [20]

The geothermal gradient [9] determines the potential use of geothermal energy. The higher the gradient, the less deep the drill needs to go [20]. Suppose the Earthship is located in an area with a suitable geothermal gradient. The only possible way to use geothermal energy in the Earthship is for the dwelling to be connected to the geothermal power plant grid. Even though the Earthship's ideology is to be independent of centralized systems, building an Earthship community with its own geothermal powerplant would benefit the dwellings. Such a community

[9] temperature increase with depth

could use the energy to heat the domestic water, produce electricity, heat up the residence, and even use it in the greenhouse. However, building a power plant is costly, and a company has to do it.

Another option is to use GSHP[10], which should not be confused with GHP[11]. GSHP uses the heat from the sun stored in the earth, the process is shown in figure 3.4 [23]. Therefore this system does not go too deep into the ground. GSHP is not dependant on a centralized energy grid; consequently, a single Earthship can have it installed. The biggest issue of having GSHP is the electricity supply to run the heat pump. If such a system is installed in an Earthship built in a colder climate without much sunlight, wind turbines or hydropower could be used to provide electricity for the pump. Installing GSHP does not have to be a necessary part of the Earthship design; however, it could be an alternative for Earthships in cold climates.

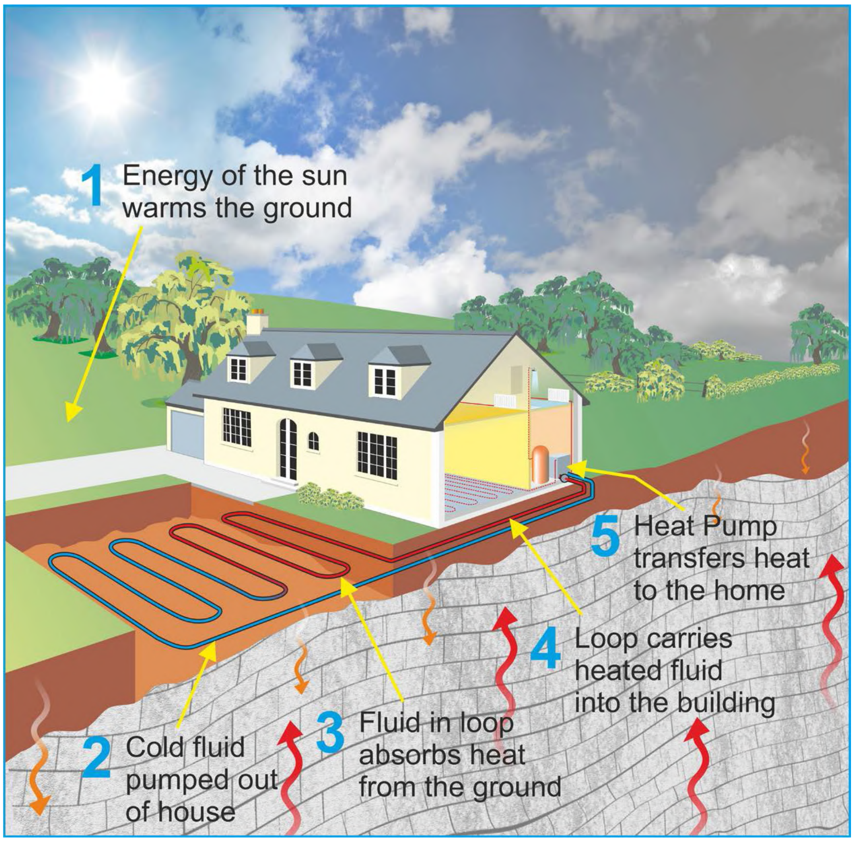


Figure 3.4: Ground source heat pump process [23]

Despite its limitations, geothermal energy or energy from the ground could be incorporated into the Earthship's design, or at least the opportunity should be explored. Even some Czech Republic and Slovakia areas might be suitable for geothermal power usage and are yet to be investigated [24] [25].

[10] ground source heat pump

[11] geothermal heat pump

4 Earthship systems

4.1 Domestic water systems - collection and distribution

Water is fundamental to all life on the planet. It covers about 71 % of Earth's surface, and only 1 % of it is freshwater, and of this, only 1 % is suitable for human consumption [26]. Even though water is precious, people lead very water-intensive lives nowadays. Water shortage is an increasing problem among the countries globally; therefore, the Earthship's idea is to have features to enable individual dwellings to capture, purify and reuse their water. The idea is to use natural resources not as individuals but as a unit [19]. Besides using less water, the Earthship must have its water system independent of centralized energy systems. With respect to the separate water system, the water usage, its collection, and distribution must be understood and discussed in this chapter.

There are four main usages of water in most households – toilets, sinks, showers and baths, washing machines and dishwashers. Flushing the toilet represents the second-largest water consumption in a home, while showers and baths represent the largest, according to Ghisi and Mengotti de Oliviera [27]. According to EU GPP [12] criteria for flushing toilets and urinals, the full flush volume of a toilet should not exceed 6.0 l/flush [28]. If an average person flushes five times a day, the total toilet consumption per person would be a maximum of 30 l. A household of four people would then use 120 l of water per day just by flushing the toilet. This is a large volume of water. Lowering the toilet water consumption is a must when building an Earthship [19]. According to Reynold's book from 1990 [19], the use of low-flush toilets or compost toilets immediately makes a significant reduction in water usage. Surprisingly, Valencio and Golçalves' study from 2019 suggests that low-flush toilets do not decrease the total water use and may result in increased water use [29]. The study found out that low-flush toilets clog more often than regular toilets resulting in a higher frequency of flushes per day. The present study raises the possibility that a standard toilet complying with the newest criteria could be used in the Earthship without using as much water as in the past. A correlation between shower water consumption and pollution may be explained in this way: pollution and dust make both people and their clothes dirty, so having less pollution would allow people to use less water to stay clean [19]. In addition to that, cutting the time one spends in the shower in half would lower the water usage, but it requires individuals to be conscious about their water consumption. Another way to reduce water consumption is not to run water while people shave or soap themselves. Bathroom and kitchen sinks can also have less impact on water usage by individuals being conscious of how much water they leave running while soaping dishes. Having water running in the sink all the time creates more sewage water to deal with and less water to use [19].

According to Reynolds, the standard Earthship design does not support having a dishwasher as it is expensive and energy-wise demanding [19]. On the contrary, Richter's study from 2011 had been able to demonstrate that the households with dishwasher used on average 50 % less water and 28 % less energy per cleaned item compared with households not owning a dishwasher [30]. According to that it can be said both a washing machine and a dishwasher may be used in the Earthship.

Water can be collected in various ways, but there two main techniques to collect water in the Earthship – using a conventional well or catching water in a cistern [19]. The conventional well requires electricity to pump water from the well. A solar well and cistern is a system where the water is pumped into a cistern using solar power. The pumping process only occurs during the

[12]Green Public Procurement

day while the sun is out, filling up the cistern. This system doesn't create a surge since there is no turning on and off the pump. The water is pumped from the cistern into a conventional pressure tank which pressurizes the water lines for domestic use. There is no need for battery storage of electricity since the electricity is directly used for pumping while the sun is out. This method has become a standard way of obtaining water for off-the-grid dwellings [19]. There is a way to eliminate one of the electric pumps and the pressure tank using a gravity cistern. If the Earthship is built on a slope, the cistern can be placed up the hill, and when the solar pump fills up the cistern, the gravity can deliver the water to the Earthship. Having discussed various power sources, if the site allows a different power system that generates enough electricity for the pump, another source of electricity can be used instead of solar energy.

Besides collecting water from a well, catching water from different sources is an option. Runoff water can be caught in a reservoir or a cistern [19]. The cistern needs to be located as high as possible and the plumbing as low as possible so that gravity can carry the water into the Earthship. This method has to be thought out before site selection. With conservative water use, this system can satisfy the individuals' water needs, even in areas with only occasional rainfall. There is a need to purify this water since the runoff contains dirt and gravel. This can be done by building small damp in front of the reservoir, which would collect all the dirt and let the water continue to the cistern [19]. Another way to do this is to build a rock barrier that would filter the water through the rocks. These cisterns are suitable for cold climates on the south-facing slopes because they can catch melting snow. On the north slopes, the ice and snow evaporate before melting. In-line filters are required to filter the water from the cistern; however, they require little electricity. In areas with moderate rainfall, enough water for domestic use can be caught [19]. Collecting roof runoff is much easier and more economical than collecting ground surface runoff. The collected water runs to the storage tank, partially submerged into the ground to create thermal mass. The water is then pumped into the Earthship through an underground line (below frost level) with a small solar pump. An in-line filter is required. There is also a possibility of catching water from snow, but the Earthship's standard design has to be slightly modified to do that. The roof's sloping has to be directed to the south because the snow melts faster on the south-facing slopes [19].

All of these techniques can collect enough water for domestic use, and it is up to the owners of the Earthship to decide the purpose of the collected water. It may be used for appliances, toilets, showers, or sinks; nevertheless, it may serve as a drinking water source. Suppose collected water is chosen to be drinking water. In that case, a drinking water filter needs to be installed in the water harvesting system as well as testing the water suitability for drinking [19].

In summary, findings from this chapter contradict the original Earthship design. The contradiction in the design is caused by technology development since the trademarked Earthship design dates back to the 1990s, and science has made progress since then. Regardless of that, water-consciousness is an integral part of designing the Earthship and living in it.

4.2 Wastewater processing

Generally, conventional houses mix blackwater and greywater together, resulting in more wastewater to treat. After the treatment, the wastewater is usually pumped out to the sea [8]. To understand the inefficiency of this process, which takes energy, the nature of blackwater and greywater must be explained. The Earthship concept states that there is no such thing as wastewater in the dwelling, and all the water used in the Earthship must be recaptured and reused [19].

Blackwater [13] is the wastewater from the toilets. The issue with blackwater is that people nowadays mix their feces with water creating waste that needs treatment before it is put back into the earth. Sewage is potentially more harmful than greywater since it contains a rich mixture of nutrients. Section 4.1 mentioned the usage of low-flush or compost toilets with regard to water usage. As a matter of fact, Reynolds's book suggests that using these types of toilets results in lowering the amount of blackwater [19]. Using compost toilets is the best solution concerning the blackwater as these toilets do not create any. Low-flush toilets produce less wastewater per flush. However, section 4.1 showed that low-flush toilets' overall water use is not less than the standard toilets' water use [29]. These results provide further support for the hypothesis that low flush toilets produce at least the same amount of blackwater as traditional toilets. Regardless of the toilet choice, the blackwater must be separated from greywater to minimize pollution.

In the case of Earthship having a conventional toilet, the blackwater treatment needs to be addressed. There are different eco-friendly ways of treating blackwater nowadays, but the original Earthship design has a small septic tank [19]. Having small septic and storing sewage in it for a more extended time allows the solids and the toilet paper to turn into a thick sludge. The septic tank is placed underground, and it has an inlet and an outlet, shown in figure 4.1. When the tank fills up, the liquid starts to flow out of the outlet into the drain field. As time passes, the sludge is turned into a natural earth product by bacteria. However, mixing black water with greywater kills the bacteria that digest the sludge [19]. An alternative way of treating sewage is by using reed beds[14]. Some Earthships use this technique [8]. The sludge is pumped through the reed bed, where it gets cleaned by microorganisms living at the system's roots. These organisms take nutrients from the sludge and use it for reed growth. Sludge reducing methods such as reed beds can treat different types of sludge, and it is also cost and energy effective [31].

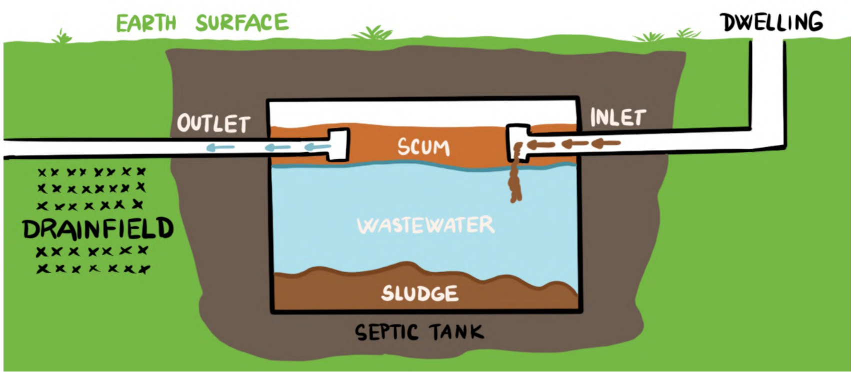


Figure 4.1: Underground septic tank diagram. Redrawn from [19] [32]

Greywater is the wastewater from sinks, showers, baths, washing machines, etc. As long as it is not mixed with blackwater, greywater can be captured and reused. One of the design features of the Earthship is to treat wastewater with plants [8]. The greywater contains nutrients for the plants. It can be collected in a cistern (separate from sewage) and later used in outdoor botanical cells or drained into the greenhouse [8]. Nonetheless, reusing water comes with responsibilities, such as being aware of what goes down the drain. The most prominent

[13] sewage

[14] common reed plant colonising open water or a wet ground

collector of organic matter in the Earthship is the kitchen sink [19]. If no harmful chemicals are put down the kitchen sink, the kitchen sink's greywater provides excellent plants' nutrients. The same principle applies to showers, bathroom sinks, and washing machines. Strong bleaches and detergents cannot be used because they kill the anaerobic process in the greywater tank [19].

The main conclusion that can be drawn is that sewage and greywater must be kept separate. Living in the Earthship requires being conscious of chemicals used in the household, meaning that only eco-friendly and natural detergents and soaps are allowed."Water recycling is a statement of how important water is as a resource" [8].

4.3 Hot water systems

Perhaps the greatest challenge in building a sustainable dwelling is the production of inexpensive hot water of constant temperature [5]. Since solar energy plays a vital role in the Earthship concept, the hot water systems are no exemption. The most common ways of obtaining hot water in the Earthship are using gas demand heaters or solar thermal energy [5]. Nonetheless, there are alternative ways of heating water for domestic use, such as using biomass boilers.

One of the simplest means of harnessing the sun's energy is solar thermal energy generation [2]. Solar thermal energy is used to heat domestic water in the Earthship. It is an excellent way of using solar energy because it is collected by a solar collector/ solar thermal unit [19]. It is then directly transferred into heat with no power generated. The solar collector is made of a black heat-absorbing plate with various pipelines running through it, allowing water to flow through the unit. The black plate allows the radiation from the sunlight to be absorbed and transferred into heat because black bodies have an absence of reflection. When the cold water enters the collector, it heats up, rises, and it is replaced by the cold water from the bottom of the water tank. The heated water flows out of the collector through an immersion heater directly into the water outlet, and it is ready to use. This process is shown in figure 4.2 [2]. Solar thermal systems rely on the power of the sun to warm the water; in regard to this, the location of the Earthship is crucial. The solar thermal system can provide hot water all year round for the Earthships built in the southern hemisphere; however, it cannot exclusively supply hot water all year round for the Earthships located in the northern hemisphere [8].

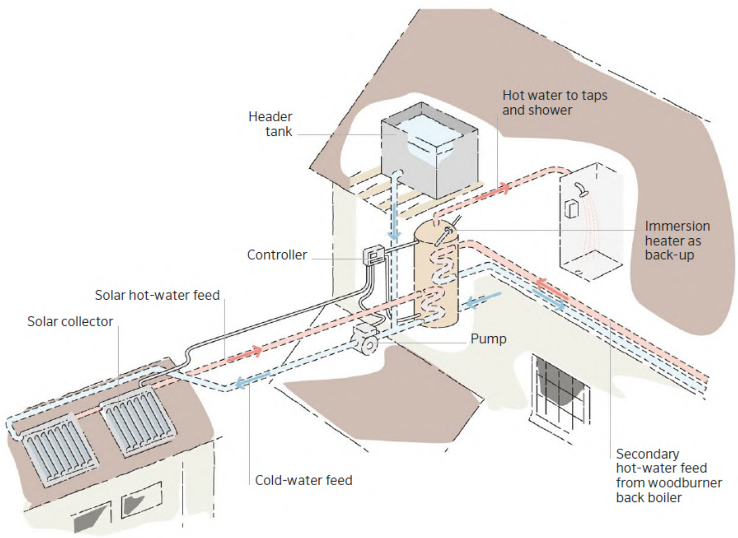


Figure 4.2: An example of a thermal setup using solar thermal collector [2]

Another way of heating water is to use an instant-on gas demand heater. This type of heater heats the water in a coil whenever someone turns the tap on. The water is passed through a flame in a copper coil. As long as the faucet is on, the fire remains on as well. This water heating method is thrifty since only the amount of water used at a given time is heated, so there is no hot water to waste. The instant-on gas demand heater requires the water to pass through an effective filter since any impurities could clog the coil [19]. The heater operates on natural gas or propane. Having a gas demand heater in the Earthship goes against the idea of not being a part of centralized systems since it integrates with the city grid. Therefore, it is instead an additional hot water system. The disadvantage of having a gas heater is the limitation in the number of fixtures – the heater is too small to service more than one fixture at a time (no dishwashing while showering) [5].

The preferred hot water system to have in an Earthship is the combination of solar thermal hot water and the gas demand heater. This solution allows the dwelling to use hot water whenever it is sunny outside and to use the heater during rainy or cloudy days [5].

5 Earthship study model

A part of the assignment of this thesis is to assess the energy balance of an Earthship. To do that, an Earthship study model had been chosen to carry out the calculations for. The chosen Earthship is called Zeměnka, and it is located in Sázava, Czech republic. NGO[15] Zemeloď built the Earthship under the guidance of Michael Reynolds. All information used for calculations and the technical documentation are available on the Earthship's website. The vessel is build with straight row arrangement. It has two rooms – eastern and western room – and a bathroom, shower and a greenhouse. According to the website, the western room is not inhabited. This Earthship is the first of its kind in Central Europe, and it is intended for testing in this climate. Figures 5.2, 5.3 and 5.4 show different views of the construction and figure 5.1 show the Earthship. The load-bearing wall is made of tires and wall's thickness is 500 mm. The floor and the roof are insulated. The dwelling is covered with soil on the circumference except for the front area with large windows.

Figure 5.1: Earthship Zeměnka [33]

[15]Non-Governmental Organisation

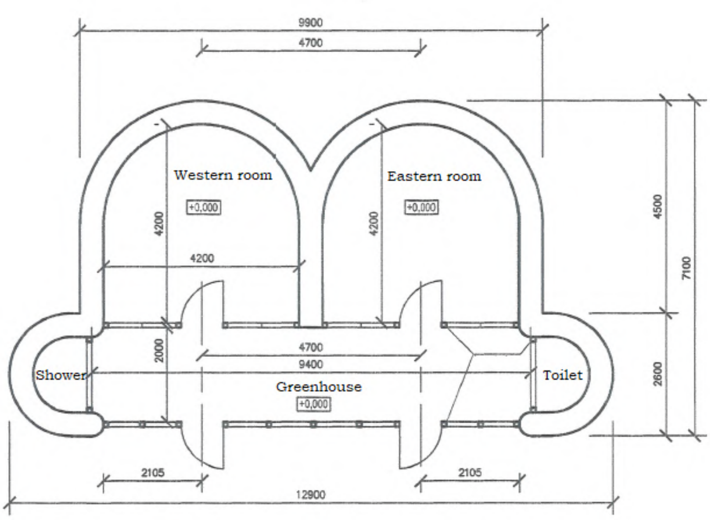


Figure 5.2: Zeměňka Earthship floor plan [34]

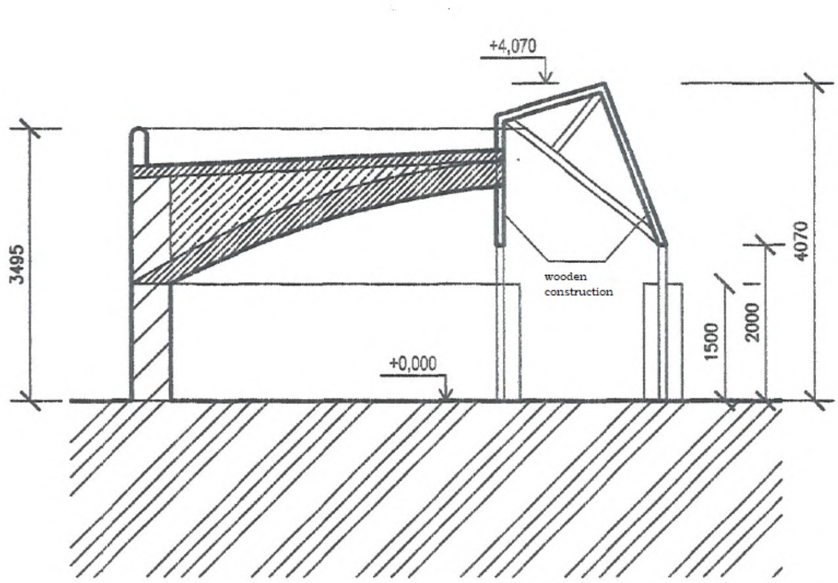


Figure 5.3: Zeměňka Earthship slice view [34]

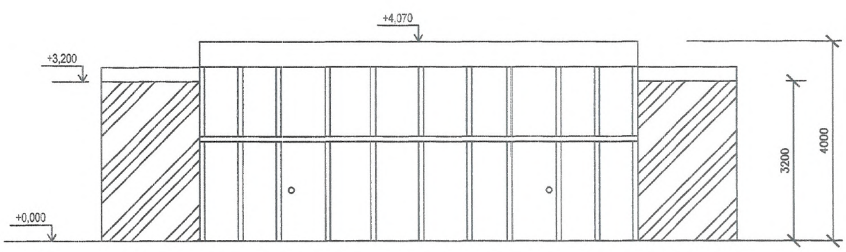


Figure 5.4: Zeměňka Earthship south view [34]

6 Energy balance of Earthship

Any energy balance is a relation between the total energy entering the system and the total energy leaving the system [35]. Generally speaking, the energy balance of a building or dwelling is the relation between heat losses and gains, shown in figure 6.1. The Earthship gains heat from the sun and the interior. The internal heat gains come from different sources, essentially anything inside the dwelling that produces heat, such as humans, pets, appliances. The heat is lost through ventilation and transmission through the walls.

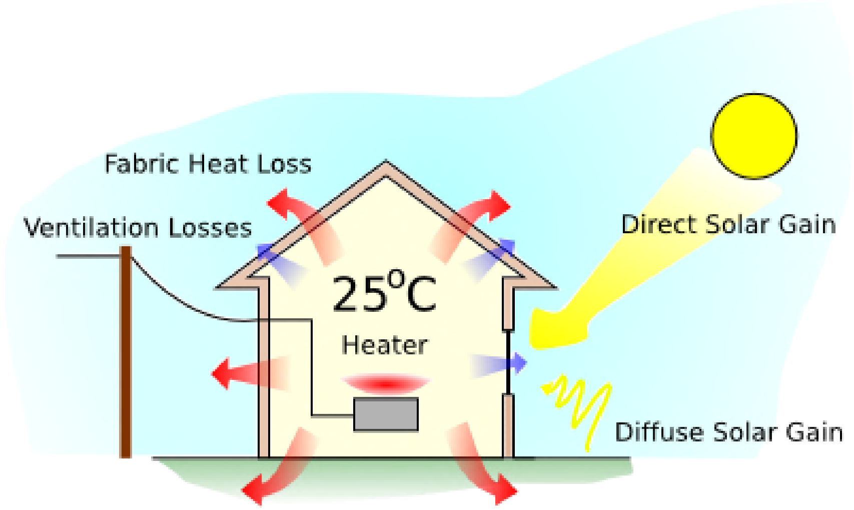


Figure 6.1: Heat balance of a building [36]

The Earthship's main design principle is to be a passive solar house, which means that the dwelling aims to cover the heat losses with solar heat gain and thermal mass. Often, the design performance of the passive solar house can deviate from reality. Since the Earthship concept is based on passive solar design, there are several performance criteria it must meet [37] [38]:

- the theoretical heat demand should not exceed 15 kWh per square meter of net living space (heated floor area) per year or 10 W per square meter peak demand.
- the total energy consumption should not exceed 120 kWh per square meter per year
- a maximum of 0.6 air changes per hour at 50 Pascal pressure
- not more than 10 % of the hours in a given year over 25 °C

The energy balance calculation of a low-energy or passive house is not meant to determine the design of the heating and cooling system but to classify the building [38]. Such energy balance can be estimated according to ČSN EN 12831-1 and ČSN 73 0548 standard [39] [40].

This chapter aims to estimate the energy performance of a chosen Earthship study model and to conclude the results. The calculation procedure to obtain the energy need for space heating of the building zone is summarized in the following list:

- estimation of thermal transmittance and climate conditions
- calculation of heat transfer by transmission
- calculation of heat transfer by ventilation

- calculation of internal heat gains
- calculation of solar heat gains

6.1 Heat transfer resistance

The heat transfer resistance of a structure element with different material layers provided one-dimensional heat flow can be calculated according to ČSN EN ISO 6946 standard [41], using equation (6.1).

$$R = \sum_{j=1}^{n} \frac{d_j}{\lambda_j} = \sum_{j=1}^{n} R_j \qquad [\frac{m^2 \cdot K}{W}] \quad (6.1)$$

where:

j thickness of the j-th layer of the material $[m]$

λ_j thermal conductivity of the j-th layer of the material $[\frac{W}{m \cdot K}]$

n number of layers of the material $[-]$

R_j heat transfer resistance of the j-th layer of the material $[\frac{m^2 \cdot K}{W}]$

The heat transfer resistance of the structure element can be calculated according to [41], using equation (6.2).

$$R_{tot} = R_{si} + \sum_{j=1}^{n} R_j + R_{se} \qquad [\frac{m^2 \cdot K}{W}] \quad (6.2)$$

where:

R_{si} internal resistance of heat transfer $[\frac{m^2 \cdot K}{W}]$

R_{se} external resistance of heat transfer $[\frac{m^2 \cdot K}{W}]$

The values of heat transfer resistances provided two-dimensional heat flow are established in [41], and the data is displayed in table 6.1.

Table 6.1: Two-dimensional heat flow heat transfer resistances

Heat transfer resistance $[\frac{m^2 \cdot K}{W}]$	**Direction of heat flow rate**			
	upward	horizontal	downward	contact with ground
R_{si}	0.1	0.13	0.17	0
R_{se}	0.04	0.04	0.04	0

Considering the nature of the Earthship structure, the choice of design thermal conductivity of soil is crucial. Different sources provide different values of thermal conductivity of soil, shown in table 6.2. Existing European and Czech standards that provide calculation methods of heat transfer through construction elements in contact with the ground are very complicated, confusing, and do not account for all possible contact arrangements [42]. The thermal conductivity values of soil, gravel, and clay were chosen from table A.1 in ČSN 730548-3 standard [43].

Table 6.3 shows thermal conductivity values of materials used in the Earthship study model. The values were obtained either from ČSN 730548-3 standard [43] or manufacturer's website. It is important to note that an assumption that the walls in the Earthship are not cylindrical had been made to simplify the calculation of heat transfer resistance.

Table 6.2: Different thermal conductivity values

Material	ČSN 730540	ČSN EN ISO 13370	ČSN EN 12831-1	Engineering toolbox
	λ	λ	λ	λ
	$\left[\frac{W}{m \cdot K}\right]$	$\left[\frac{W}{m \cdot K}\right]$	$\left[\frac{W}{m \cdot K}\right]$	$\left[\frac{W}{m \cdot K}\right]$
Dry clay	0.45			
Sandy soil with natural humidity	0.85			
Wet sandy soil	2.3			
Clay		1.5		1.1
Sand and gravel		2		0.7
Homogeneous rocks		3.5		
Soil			2	
Saturated soil				0.6
Soil with organic matter				0.15

Table 6.3: Thermal conductivity values of materials used in Zeměnka Earthship

Construction material number	**Description**	λ $\left[\frac{W}{m \cdot K}\right]$
1	Natural rubber	0.16
2	Rammed soil	0.85
3	Reinforced concrete	1.22
4	Concrete	1.05
5	Gravel	0.58
6	Clay	0.45
7	Chipboard	0.17
8	Stone tile	1.01
9	Polyiso insulation	0.023
10	Styropor insulation	0.038

6.2 Transmission heat loss coefficient

The transmission heat loss coefficient or thermal transmittance value is the total heat transfer between two environments divided by a specific heat transfer resistance structure. It can be calculated based on [41] using equation (6.3).

$$U = \frac{1}{R_{tot}} \qquad [\frac{W}{m^2 \cdot K}] \quad (6.3)$$

Similarly, the thermal transmittance value of a structure element in contact with the ground or equivalent transmission heat loss coefficient is calculated in a more complicated way according to [39]. However, there is a simplified calculation method which uses equation

$$U_{equivalent} = \frac{1}{R_{tot} + \frac{1}{\lambda_g}} \qquad [\frac{W}{m^2 \cdot K}] \quad (6.4)$$

where:

λ_g thermal conductivity of soil $[\frac{W}{m \cdot K}]$

The different transmission heat loss coefficients had been calculated using MS Excel; however, the coefficients values of windows and doors are obtained from table B.15 in [39] and they are shown in attachment 1.

6.3 Climate data

The climate input data is determined according to ČSN EN 12831-1 standard [39], specifically table NA.1. The data is provided for meteorological stations; therefore, the closest one to Sázava had been chosen. Figure 6.2 shows different temperature zones across the Czech republic and the Zeměnka Earthship is situated in the orange area.

Figure 6.2: Czech republic climate map
blue - cold climate (-18 °C), yellow - mild climate (-15 °C), orange - warm climate (- 12 °C)

Table 6.4: Climate data for Kutná Hora (Kolín) [39]

	θ_e	$\theta_{m,e}$	$\theta_{int,build}$	d	θ_{gr}
Kutná Hora (Kolín)	- 12	4	20	216	5

where:

θ_e design outdoor temperature [°C]

$\theta_{m,e}$ average outdoor temperature during heating period [°C]

$\theta_{int,build}$ design interior temperature of building space obtained from table NA.3 [39] [°C]

d number of days in heating period $[-]$

θ_{gr} soil (adjacent to the building structure) temperature in winter obtained from table H.5 [43]

6.4 Transmission heat loss

To calculate the transmission heat loss of the Zeměnka Earthship, the heat flow paths need to be understood. The Earthship two heat flow options: heat flow into the ground and direct heat flow into the exterior. The ČSN EN 12831-1 standard [39] does not provide a calculation method for a building covered with earth on its circumference; therefore, slight modifications to the calculation had been done. When calculating the heat transmission of a structural element in contact with the ground, the temperature difference between the interior and the ground is considered since the soil has a steady temperature during winter, unlike the exterior [43]. The external dimensions of the Earthship determine the thermal envelope of the building zone. The standard [39] estimates the heat loss during heating period for the lowest outdoor temperature for the given area. Thermal bridges had been neglected to simplify the calculation's nature and to remain in the thesis's range. The total transmission heat loss can be calculated according to [39], using equation (6.5).

$$\Phi_{T,build} = (H_{T,g} + H_{T,e}) \cdot (\theta_{int,build} - \theta_e) \qquad [W] \quad (6.5)$$

where:

$H_{T,g}$ heat transfer coefficient from heated space into the ground $[\frac{W}{K}]$

$H_{T,e}$ heat transfer coefficient from heated space into exterior $[\frac{W}{K}]$

$\theta_{int,build} - \theta_e$ difference between interior temperature and the temperature on the external surface of the construction; in contact with soil $\theta_e = \theta_{gr}$ [°C]

Heat transfer coefficient from heated space into the ground $H_{T,g}$

To calculate the heat transfer coefficient from heated space into the ground, the equivalent transmission heat loss coefficient is used.

$$H_{T,g} = f_{g1} \cdot f_{g2} \cdot (\sum_k A_k \cdot U_{equivalent,k}) \cdot G_W \qquad [\frac{W}{K}] \quad (6.6)$$

where:

A_k area of construction element $[m^2]$

f_{g1} correction factor taking into account the annual temperature changes; $f_{g1} = 1.45$ $[-]$

f_{g2} temperature correction factor $[-]$

$$f_{g2} = \frac{\theta_{int,build} - \theta_{m,e}}{\theta_{int,build} - \theta_e} = 0.5 \quad (6.7)$$

G_W correction factor taking into account the effect of groundwater; $G_W = 1$ $[-]$

Heat transfer coefficient from heated space into exterior $H_{T,e}$

The heat transfer coefficient from heated space into exterior is calculated according to [39], using equation (6.8).

$$H_{T,e} = \sum_k (A_k \cdot U_k \cdot e_k) \qquad [\tfrac{W}{K}] \qquad (6.8)$$

where:

e_k correction factor taking into account the effect of the structure element properties that had been ignored in U-value calculation; $e_k = 1$ in order to simplify the calculation $[-]$

The transmission heat loss of the Earthship had been calculated using MS Excel and the results are shown in figure 6.3.

ZEMĚNKA EARTHSHIP

Heat transfer coefficient into exterior

Label	Construction element	$A_k\,[m^2]$	$U_k\,\left[\frac{W}{m^2 \cdot K}\right]$	$e_k\,[-]$	$A_k \cdot U_k \cdot e_k$	
B	Roof	58.43	0.61	1.00	35.59	
C	Windows and doors	38.26	1.30	1.00	49.74	
$H_{T,ie} = \sum_k A_k \cdot U_k \cdot e_k \left[\frac{W}{K}\right]$						85.32

Heat transfer coefficient into the ground

Label	Construction element	$A_k\,[m^2]$	$U_k\,\left[\frac{W}{m^2 \cdot K}\right]$	$f_{g1}\,[-]$	$f_{g2}\,[-]$	$G_W\,[-]$	$A_k \cdot U_k$	
A	External load-bearing tire wall	65.03	0.45	1.45	0.50	1.00	29.27	
D	Floor	69.50	0.15				10.29	
$H_{T,ig} = f_{g1} \cdot f_{g2} \cdot (\sum_k A_k \cdot U_k) \cdot G_W \left[\frac{W}{K}\right]$								28.68
TOTAL TRANSMISSION HEAT LOSS IN THE EARTHSHIP						3160.60		

Figure 6.3: Transmission heat loss in Zeměnka Earthship

6.5 Ventilation heat loss

One of the sailing principles of the Earthship is to control the room temperature with natural ventilation. The ČSN EN 12831-1 standard [39] differentiates between natural and forced ventilation. Therefore the ventilation heat loss of the Earthship had been computed for a natural ventilation system, using simplified method, equation (6.9).

$$\Phi_{V,build} = H_V \cdot (\theta_{int,build} - \theta_e) \qquad [W] \qquad (6.9)$$

where:

H_V ventilation heat loss coefficient $[\frac{W}{K}]$

Ventilation heat loss coefficient

$$H_V = 0.34 \cdot \dot{V} \qquad [\tfrac{W}{K}] \qquad (6.10)$$

where:

$\dot{V}$ air change rate; $\dot{V} = max(\dot{V}_{inf}, \dot{V}_{min})$ $[\frac{m^3}{h}]$
where:

$\dot{V}_{inf}$ infiltration air change rate $[\frac{m^3}{h}]$

$\dot{V}_{min}$ hygienic amount of air change $[\frac{m^3}{h}]$

Hygienic amount of air change

Due to hygiene, the minimum amount of hygienic air change rate is required.

$$\dot{V}_{min} = n_{min} \cdot V \tag{6.11}$$

where:

n_{min} the minimum intensity of air change rate according to [39]; $n_{min} = 0.5$ for living space

V space volume $[m^3]$

Infiltration air change rate

The infiltration air change rate is the amount of air infiltrating the building due to wind and pressure.

$$\dot{V}_{inf} = 2 \cdot V \cdot n_{50} \cdot e \cdot \varepsilon \tag{6.12}$$

where:

n_{50} intensity of air change rate per hour at pressure difference of 50 Pa between the interior and the exterior of the building; $n_{50} = 0.6$ according to passive house criteria $[\frac{m^3}{h}]$

e shading coefficient; $e = 0.05$ for space with more windows according to [39] $[-]$

ε correction height factor according to [39]; $\varepsilon = 1$ for a space of a height between 0 and 10 m $[-]$

The ventilation heat loss of each room had been calculated using MS Excel and it is shown in figure 6.4.

Space				Minimum hygienic requirements						Ventilation heat loss			
	Room volume	Design outdoor temperature	Design indoor temperature	Minimum hygienic intensity of air change	Minimum hygienic amount of air	Air change intensity at 50 Pa	Shading coefficient	Height coefficient	Infiltration air amount	Design calculation value	Design ventilation heat loss coefficient	Temperature difference	Ventilation heat loss
	V $[m^3]$	$\theta_e [°C]$	$\theta_{int} [°C]$	$n_{min} [h^{-1}]$	V_{min} $[m^3/h]$	n_{50} $[h^{-1}]$	e $[-]$	ε $[-]$	V_{inf} $[m^3/h]$	$\dot{V} [m^3/h]$	H_V $[W/K]$	$[°C]$	Φ_V $[W]$
Earthship	208.5	-12	20	0.5	104.25	4.5	0.05	1	93.825	104.25	35.445	32	1134.24
TOTAL VENTILATION LOSS IN THE EARTHSHIP													1134.24

Figure 6.4: Ventilation heat loss in Zeměnka Earthship

6.6 Solar heat gain input parameters

The solar heat gain calculation is carried out according to ČSN 73 0548 standard [40]. Specific input parameters need to be calculated before the heat gain calculation. The calculated input parameters are shown in attachment 2.

(a) **Declination of the Sun δ**
Declination of the Sun is the angle between the rays of the Sun and the plane of the Earth's equator. It is calculated using equation (6.13) and it is always calculated for the 21_{st} day of the month.

$$\delta = -23.5cos(30M) \qquad [°] \quad (6.13)$$

where:

M month number (1-12)

Table 6.5: Declination of the Sun of different months [40]

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
δ [°C]	-20.4	-11.8	0	11.89	20.4	23.5	20.4	11.8	0	-11.8	20.4	-23.5

(b) **Altitude of the Sun above the horizon h**
Given for 50° latitude (Czech republic) and calculated using equation (6.14).

$$sinh = 0.766 \cdot \delta - 0.643 \cdot cos\delta \cdot cos(15\tau) \quad (6.14)$$

$$h = arcsin(0.766 \cdot \delta - 0.643 \cdot cos\delta \cdot cos(15\tau)) \qquad [°] \quad (6.15)$$

where:

τ solar time (specific calculation hour) $[h]$

(c) **Outdoor temperature profile θ_e**

$$\theta_e = \theta_{e,max} - A[1 - sin(15\tau - 135)] \qquad [°C] \quad (6.16)$$

where:

$\theta_{e,max}$ maximum temperature during the day; recommended values of different months are given in tab.1 in [40], however, the heating period months are not included in this standard, therefore temperature data provided by CHMI[16] had been used [°C]

A amplitude of outdoor temperature fluctuations; $A = 7$ $[K]$ according to [40]

(d) **Solar azimuth a**

$$sina = \frac{sin(15\tau) \cdot cos(\delta)}{cosh} \quad (6.17)$$

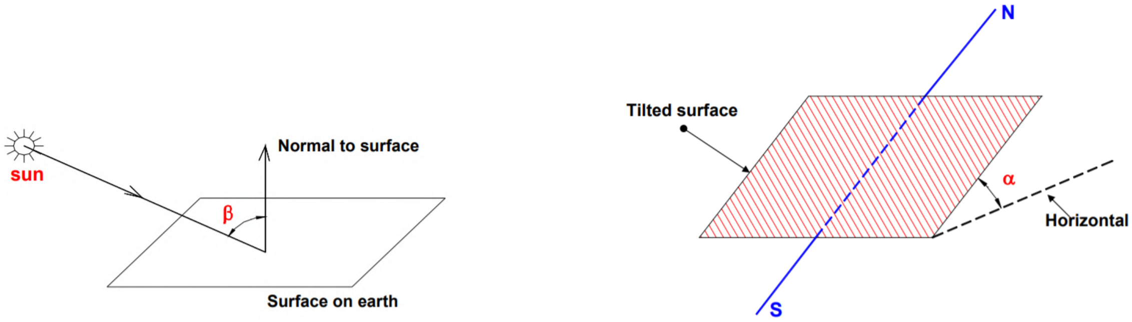
The values are obtained from table 4 in [40].

(e) **Angle of incidence β**
The angle of incidence is the angle between the normal of irradiant surface an the direction of the sun rays, shown in figure 6.5.

$$cos\beta = sinh \cdot cos\alpha + cosh \cdot sin\alpha \cdot cos(a - \gamma) \quad (6.18)$$

where:

[16]Czech Hydrometeorological Institute



(a) Angle of incidence

(b) Tilt angle of oriented surface

Figure 6.5: Definition of angles [44]

α angle between the wall and the horizontal plane; $\alpha = 90$ [°] for the vertical windows, and approximately $\alpha = 75$ [°] for tilted windows[17]

γ azimuth angle of the normal of the wall; $\gamma = 180$ [°] for south-facing wall

(f) **Direct solar irradiance intensity $\dot{I}_D$**

$$\dot{I}_D = 1350 \cdot exp[-0.1 \cdot z(\frac{16-H}{16+H}/sinh)^{0.8}] \qquad [W/m^2] \quad (6.19)$$

where:

z atmospheric pollution factor - Linke turbidity factor; $z = 2.75$ $[-]$ for off-grid area according to [45].

H elevation; $H = 0.340$ $[km]$

(g) **Diffuse solar irradiance intensity $\dot{I}_d$**

$$\dot{I}_d = [1350 - \dot{I}_D - (1080 - 1.4 \cdot \dot{I}_D) \cdot sin^2\frac{\alpha}{2}]\frac{sinh}{3} \qquad [W/m^2] \quad (6.20)$$

(h) **Direct solar irradiance intensity of an oriented surface**

$$\dot{I}_{DO} = \dot{I}_D \cdot cos\beta \qquad [W/m^2] \quad (6.21)$$

(i) **Total proportional transmittance of direct solar radiation T_D**

$$T_D = 0.87 - 1.47 \cdot (\frac{\beta}{100})^5 \qquad [-] \quad (6.22)$$

(j) **Total proportional transmittance of diffuse solar radiation T_d**
The value of total proportional transmittance of diffuse solar radiation does not change with the sun's position.

$$T_d = 0.85 \qquad [-] \quad (6.23)$$

[17]the technical drawing does not provide enough parameters to precisely calculate this angle, therefore it had been estimated

(k) **Standard window diffuse solar irradiance intensity** $\dot{I}_{d,W}$

$$\dot{I}_{d,W} = T_d \cdot \dot{I}_d \qquad [W] \qquad (6.24)$$

(l) **Total solar irradiance intensity** $\dot{I}_W$

$$\dot{I}_W = T_D \cdot \dot{I}_D + \dot{I}_{d,W} \qquad (6.25)$$

(m) **Sunlit window surface** $A_{W,S}$

$$A_{W,S} = n_W \cdot [l_1 - (e_1 - f)] \cdot [l_2 - (e_2 - g)] \qquad [m^2] \qquad (6.26)$$

where:

n_W number of windows $[-]$

l_1 height of the window; $l_1 = 2$ $[m]$ for vertical windows, $l_1 = 1.2$ for tilted windows

e_1 length of horizontal shadow on the window $[m]$

f distance of the vertical part of the window from the sunshade; $f = 0$ $[m]$

l_2 width of the window; $l_2 = 0.65$ $[m]$ and there are two windows and two doors of a width $l_2 = 0.95$

e_2 length of vertical shadow on the window $[m]$

g distance of the horizontal part of the window from the sunshade; $g = 0$ $[m]$

(n) **Length of horizontal shadow on the window** e_1

$$e_1 = d \cdot tan(a - \gamma) \qquad [m] \qquad (6.27)$$

where:

d window depth; $d = 0.1$ $[m]$

(o) **Length of vertical shadow on the window** e_2

$$e_2 = \frac{c \cdot tanh}{cos(a - \gamma)} \qquad [m] \qquad (6.28)$$

where:

c window depth relative to upper shading panel; $c = 0.1$ $[m]$ since there is no shading panel

6.7 Convection heat transfer

$$\Phi_{w,con} = U_W \cdot A_W \cdot (\theta_e - \theta_{int,i}) \qquad [W] \qquad (6.29)$$

where:

U_W transmission heat loss coefficient

A_W window are including the frame $[m^2]$

θ_e temperature profile estimated according to [40]

$\theta_{int,build}$ design interior temperature estimated according to [39] shown in table 6.4

The values of heat transfer by convection were calculated using MS Excel and are displayed in figure 6.6.

Convenction heat transfer through windows [W]															
month \ solar time	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				-1189.26	-1099	-1009	-925.1	-852.975	-797.6	-762.9	-751	-762.9			
2				-1035.08	-945	-854.9	-770.9	-698.795	-643.5	-608.7	-596.8	-608.7			
3		-644.1	-572	-487.99	-397.9	-307.8	-223.8	-151.706	-96.38	-61.6	-49.74	-61.6	-96.38	-151.7	
4		-494.9	-422.8	-338.784	-248.7	-158.6	-74.6	-2.49933	52.828	87.61	99.47	87.61	52.83	-2.499	
5	-326.4	-271	-198.9	-114.975	-24.87	65.24	149.21	221.31	276.64	311.4	323.3	311.4	276.6	221.3	149.2
6	-226.9	-171.6	-99.47	-15.5042	74.6	164.7	248.68	320.781	376.11	410.9	422.8	410.9	376.1	320.8	248.7
7	-152.3	-96.97	-24.87	59.09892	149.2	239.3	323.28	395.384	450.71	485.5	497.4	485.5	450.7	395.4	323.3
8		-96.97	-24.87	59.09892	149.2	239.3	323.28	395.384	450.71	485.5	497.4	485.5	450.7	395.4	
9		-221.3	-149.2	-65.2396	24.87	115	198.94	271.045	326.37	361.2	373	361.2	326.4	271	
10				-264.181	-174.1	-83.97	0	72.1038	127.43	162.2	174.1	162.2			
11				-1059.95	-969.8	-879.7	-795.8	-723.663	-668.3	-633.6	-621.7	-633.6			
12					-1094	-1004	-920.1	-848.001	-792.7	-757.9	-746				

Figure 6.6: Convection heat transfer values

6.8 Radiation heat transfer

$$\Phi_{w,rad} = [A_{W,S} \cdot \dot{I}_W \cdot f_o + (A_W - A_{W,S}) \cdot \dot{I}_{d,W}] \cdot f_{sh} \qquad [W] \qquad (6.30)$$

where:

f_o atmosphere correction factor; $f_o = 1.15$ for off-grid area

f_{sh} shading factor; $f_{sh} = 0.9$ for double-pane window

The radiation heat transfer is calculated separately for vertical windows and for tilted windows and the total values of radiation heat transfer are shown in figure 6.7.

Total radiation heat transfer [W]															
month \ solar time	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				1067.821	4480	7159	9155.8	9825.97	9155.8	7159	4480	822.4			
2				3177.502	6355	9136	11059	11928.2	11059	9136	6355	3178			
3		250.8	1800	4367.698	7528	10491	12445	13290.2	12445	10491	7528	4368	1539	237.1	
4		2119	1756	4463.711	7685	10559	12579	13500.1	12579	10559	7685	4464	1692	1913	
5	4621	4575	23936	3843.783	7166	9956	11917	12978	11917	9956	7166	3844	23668	3921	3200
6	7392	6055	11881	3292.575	6524	9556	11660	12703.6	11660	9556	6524	3293	11551	5106	5052
7	2674	4981	23053	3843.783	7166	9956	11917	12978	11917	9956	7166	3844	23668	3921	1866
8		2145	1755	4463.711	7685	10559	12579	13500.1	12579	10559	7685	4464	1692	1913	
9		250.9	1818	4367.698	7528	10491	12445	13290.2	12445	10491	7528	4368	1539	237.1	
10				3177.502	6355	9136	11059	11928.2	11059	9136	6355	3178			
11				822.3876	4480	7159	9155.8	9825.97	9155.8	7159	4480	822.4			
12					2705	6113	7876.8	8882.28	7876.8	6113	2705				

Figure 6.7: Total radiation heat transfer values

6.9 Total solar heat gain

The coldest month of the year in the Czech Republic is January. Ergo, the solar heat gain values for January will be considered for further calculation. If the thermal balance of the building is achieved in the coldest month of the year, then the design will work during the other months as well. The heat gain values are computed for each hour. The mean value of heat gain $\Phi_{S,mean}$ during the day in January is obtained by adding all heat gain values and diving them by the number of solar hours.

$$\Phi_{S,mean} = 3010 \qquad [W] \qquad (6.31)$$

The total solar heat gain during the day in January is shown in figure 2.8.

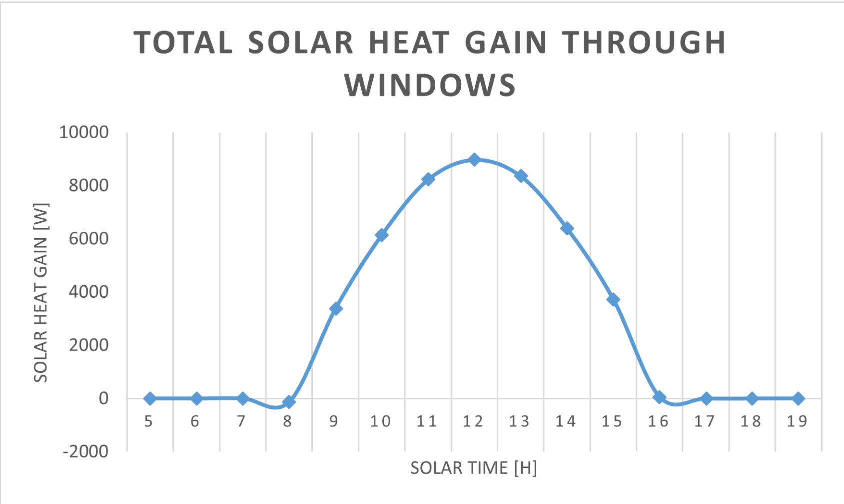


Figure 6.8: Total solar heat gain through windows in January

6.10 Internal heat gain

Internal heat gains consist of heat transfer from people and appliances or technology [40]. Since the website nor the technical documentation of Zeměnka Earthship does not provide information about the appliances and technology present in the dwelling, the estimation of internal heat gain is carried out for heat transfer from people only. The calculation is held up to ČSN 73 0548 standard, using equation (6.32).

$$\Phi_I = i_P \cdot 6.2 \cdot (36 - \theta_{int,build}) \qquad [W] \qquad (6.32)$$

where:

i_P number of people $[-]$

If the group of people living in the Earthship is made of women, children, and men, the number of people needs to be adjusted to an equivalent number since women and children produce a different amount of heat than men [40]. Equation (6.33) shows the calculation of equivalent number of people.

$$i_P = 0.85 i_W + 0.75 i_{Ch} + i_M \qquad [-] \qquad (6.33)$$

where:

i_W number of women $[-]$

i_{Ch} number of children $[-]$

i_M number of men $[-]$

The number of people living in the Earthship is estimated to be four, and the group is made of a woman, a man, and two children.

$$i_P = 0.85 \cdot 1 + 0.75 \cdot 2 + 1 = 3.35$$

The internal heat gain in the Earthship is estimated to be

$$\Phi_I = 332.3 \qquad [W] \quad (6.34)$$

6.11 Annual space heating demand

The energy consumption during heating season is converted to kWh in order to estimate the annual heating demand. The number of degree days is computed using equation (6.35).

$$D = d \cdot (\theta_{int,build} - \theta_{m,e}) = 216 \cdot (20 - 4) = 3456 \qquad [K \cdot day] \quad (6.35)$$

The correction factor ε is calculated using equation (6.36).

$$\varepsilon = \frac{e_i e_t e_d}{\eta_0 \eta_r} \qquad [-] \quad (6.36)$$

where:

e_i inconsistency of heat loss; $e_i = 0.7$ according to [46]

e_t temperature difference correction factor; $e_t = 0.8$ according to [46]

e_d time period correction factor; $e_d = 1$ according to [46]

η_0 efficiency of heating system's regulation; $\eta_0 = 0.9$ according to [46]

η_r efficiency of heating system; $\eta_r = 0.9$ according to [46]

$$\Phi_{H,a} = \frac{24 \cdot (\Phi_{total}) \cdot \varepsilon \cdot D}{\theta_{int,average} - \theta_e} \qquad [\tfrac{kWh}{year}] \quad (6.37)$$

where:

Φ_{total} total heat transfer in the building $[W]$

$$\Phi_{total} = \Phi_T + \Phi_V - \Phi_{S,mean} - \Phi_I \qquad [W] \quad (6.38)$$

$$\Phi_{total} = 3160.60 + 1134.24 - 3010 - 332.3 = 952.54 \quad [W]$$

$\theta_{int,average}$ average indoor temperature [°C]

The heating demand of Zeměnka Earthship is estimated to be

$$\Phi_{H,a} = 1707 \quad [\frac{kWh}{year}]$$

$$\Phi_{H,a} = 24.6 \quad [\frac{kWh}{m^2 year}]$$

6.12 Passive house criteria analysis

It is essential to analyze the results obtained from previous calculations. The most critical passive house requirement is that the heating demand does not exceed 15 kWh per square meter of net living space (heated floor area) per year, which had not been fulfilled since the heating demand of the model Earthship is approximately 24 kWh per square meter of net living space. The comparison of different heating demands is shown in figure 6.9 from which it can be concluded that the Zeměnka Earthship is not a passive house but a low-energy house.

The total energy consumption should not exceed 120 kWh per meter square per year in Zeměnka Earthship since the dwelling also produces electricity with solar panels to cover the consumption.

The air change rate at 50 Pa pressure was not measured in the actual Earthship, so the calculation value was obtained from ČSN 73 0540-2 standard [47]. This requirement might be fulfilled in reality; however, based on the Czech standard, it is not.

The Zeměnka Earthship website provides temperature measurements that are not taken in regular intervals, but the data available suggests that indoor temperature never exceeded 25°C.

The results obtained using the Czech standards can deviate from reality since the standards are adapted to a different type of housing. These standards do not take the accumulation of heat into consideration therefore the values can deviate from values potentially obtained, e.g., from a simulation software. Another issue of the Czech standards is the absence of complex calculation of heat transfer through an element in contact with soil [42]. If a simulation software was used, different results might have been obtained.

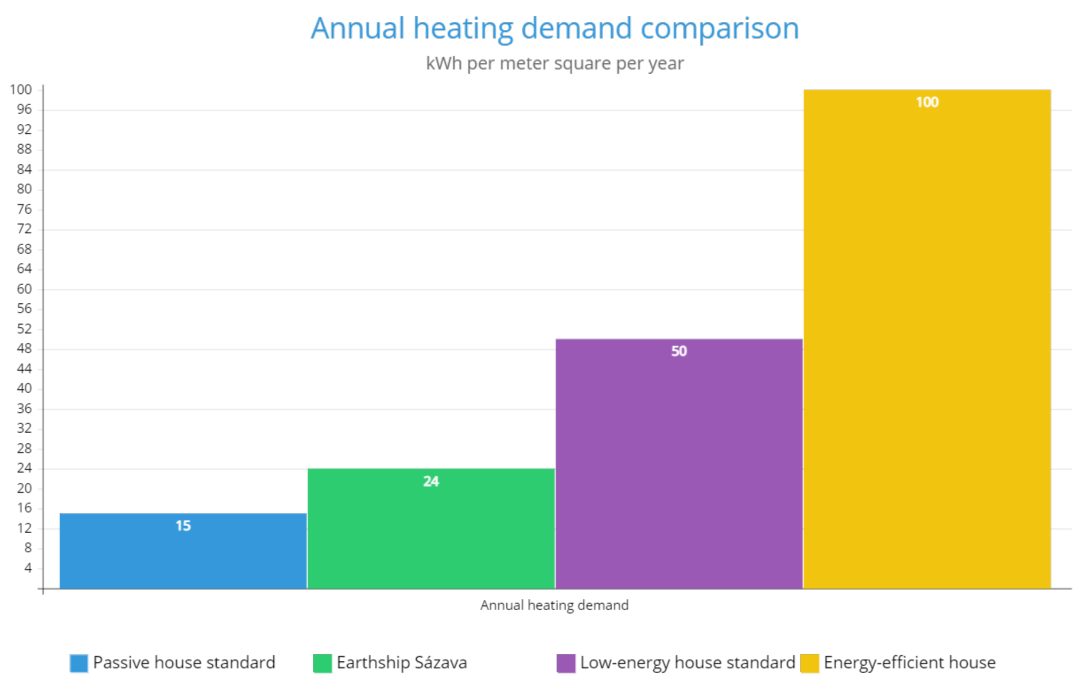


Figure 6.9: Annual heating demand comparison

7 Advantages and disadvantages

Based on the description and explanation of the Earthship concept in this thesis, it is apparent that there are advantages and disadvantages to this dwelling. The benefits and the weaknesses of the concept have been critically appraised in this chapter.

To begin with, using garbage in construction and incorporating it in the design eliminates the amount of waste on the planet, which is an advantage of this housing. The usage of renewable energy and the independence from the energy grid is distinguishable from most regular houses. The Earthship concept lowers its dwellers' carbon footprint just by using renewable energy if used correctly, which is considerably good for the environment. In addition to its benefits, the separation of blackwater from greywater is particularly innovative and significant. The Earthship's treatment of wastewater does not harm nature as much as most regular housings do. This housing's affordability is questionable since the prices range from 15 000€ to 300 000€. However, compared to the rising real estate prices per meter squared of living space, the Earthship can be considered affordable.

On the contrary to benefits, there are weaknesses to this concept. As mentioned in the introduction, the Earthship aims to be available to the masses. There is a reason to believe that a mass concept of Earthship housing worldwide is not possible. The main reason for that is that this type of housing is certainly not suitable for all climates. For example, Greenland or Svalbard are places where there are people in need of housing; however, it would get too cold in the Earthship if build there. Another reason why Earthship as a housing unit available to the masses will not work is that if everyone in the world becomes self-sufficient and sustainable, capitalism would not work or would have to adapt, which could result in different issues. Not being a part of the energy grid is a benefit and a disadvantage at the same time since there are power shortages in Earthships. Most Earthships use solar energy to produce electricity, and the sun is not a stable power source in some climates. These power shortages not only result in appliances not working or the pump not pumping the water from the well but also the internet unavailability. Plenty of people work remotely using the internet, and it is considered necessary in the 21^{st} century. Not a disadvantage per se, but the concept of self-sufficiency also fails in food production. As explained in the food production chapter, not all Earthships can grow food and, more importantly, not large amounts. The Earthship architecture might be an issue to some people since individuals have different tastes in design, and some might not want to live in a house made of garbage.

Then there is the question of whether people would be willing to live in this kind of house. The decision was taken to investigate what individuals think of living in such a dwelling. There were 97 participants in the age range 17-62 who filled out a google form questionnaire (attachment 3). It was surprising that 72.2 % of participants would be willing to lead a water-conscious life, and 84.5 % of participants would be okay with a greenhouse being a part of their house. In conclusion, 91.7 % of participants answered yes or maybe to whether they would live in a sustainable house. This indicates that humans realize the importance of change in housing, and they would live in such house if sustainable dwellings would be globally available to everyone.

In summary, the energy design of the Earthship is highly dependant on the location and the season. Some Earthships might work as passive houses others might not. However, the concept was invented in 1990s. As the technology developed, there are other concepts of sustainable living such as 3D printed autonomous intelligent houses[18]. The Earthship concept might not be the housing solution of the future but it might work for some people.

[18] more information: `https://haus.me/`

Conclusion

The development of sustainable and resource-efficient housing concept is significantly essential nowadays. All necessary information about the Earthship idea and the energy systems has been summarized and presented in this thesis. In addition to information, calculations have been conducted to look at the physics behind the concept. The last chapter showed that the disadvantages outweigh the benefits of owning the Earthship and living it.

The research part of the thesis showed that there are limitations to the concept. It is important to note that Reynolds believes that tapping into the earth's warmth provides comfort in any climate [1]. His conclusions might be based on the Earthships in New Mexico where the concept works, but the European climate is not so suitable. Some European builds have had problems with mold and moisture [8]. Nonetheless, Reynolds refuses to provide research to support his claim that the concept works anywhere [48]. So the most significant issue of the Earthship is that it does not work in any climate. For example, an Earthship in Spain had encountered overheating during the summer, and the owners had to adapt the design [48]. This statement is also supported by the results of the energy balance calculation in this thesis. Even though the calculation was simplified, the result showed that the Earthship in Sázava is not a passive house, and there is a need for additional heating during winter. The data provided by Earthship Sázava owners support this conclusion since it shows that the indoor temperature without heating during winter is around 10 – 11 °C. Thermal comfort in the Earthship is not guaranteed everywhere indeed. The thesis also described the problems with the instability of renewable energy sources and water sufficiency. However, all limitations that might occur in the Earthship result from the most significant one being the suitability of the concept for any climate.

Ultimately, the Earthship concept is not a ground-breaking solution to the environmental crisis. The design's marketing might be better than the concept itself. There are always weaknesses to any kind of housing concept, but the Earthship has many of them. However, the construction industry should follow Earthship's message to start using indigenous and recyclable materials to lower its carbon footprint. There is no ideal solution to provide sustainable living, and if there was one, it could result in economic and political issues. Ergo, it is hard to say what is the best course of action against climate change.

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